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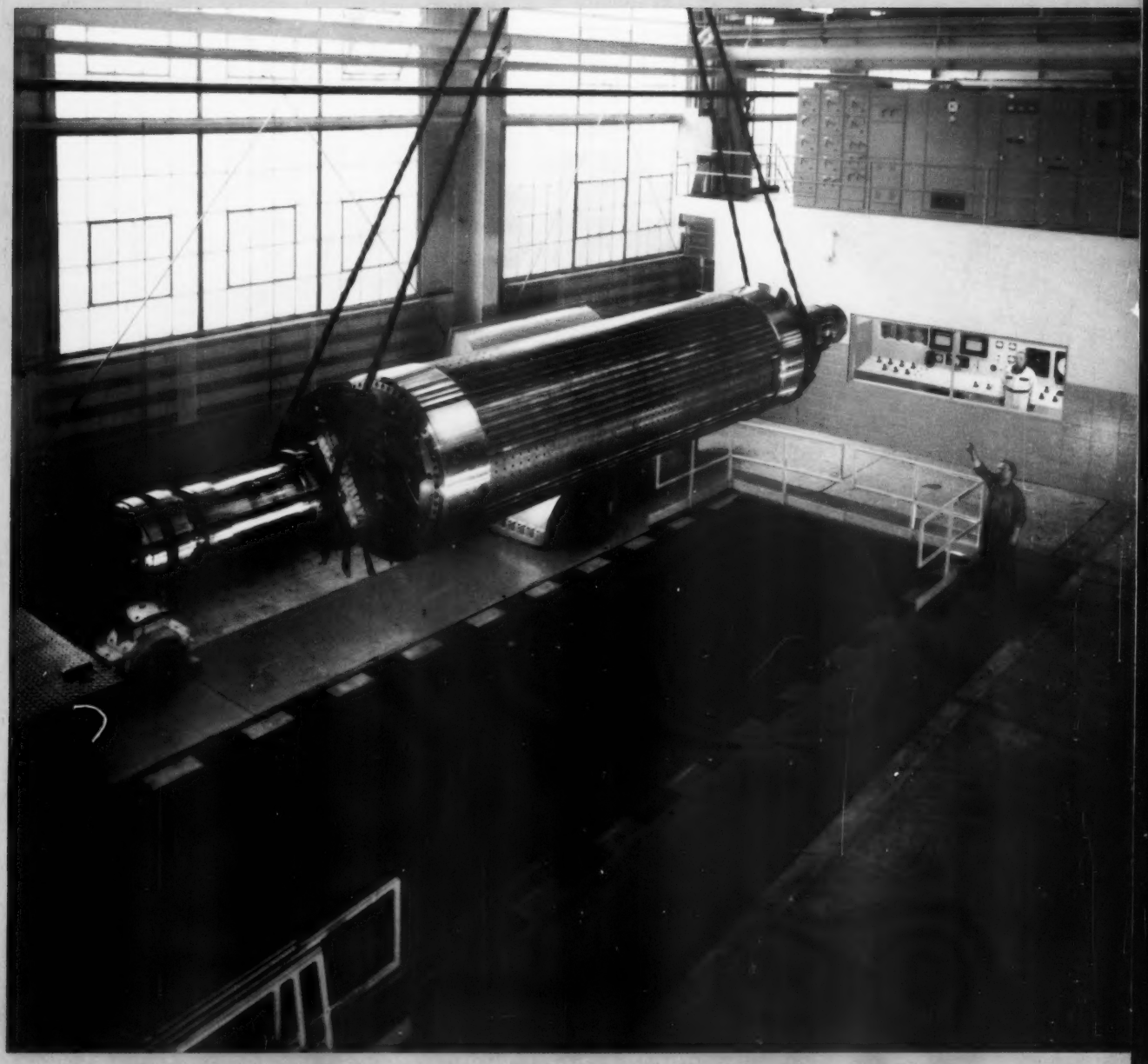
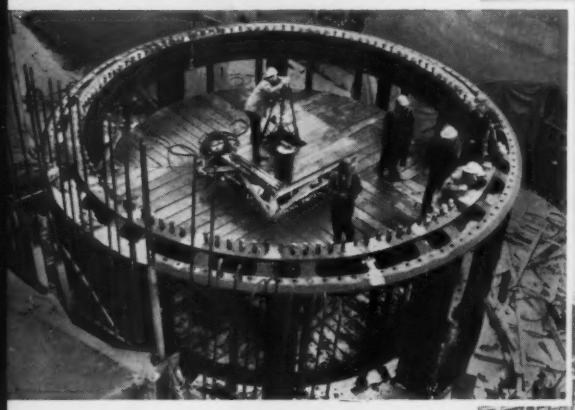
ALLIS-CHALMERS Electrical REVIEW

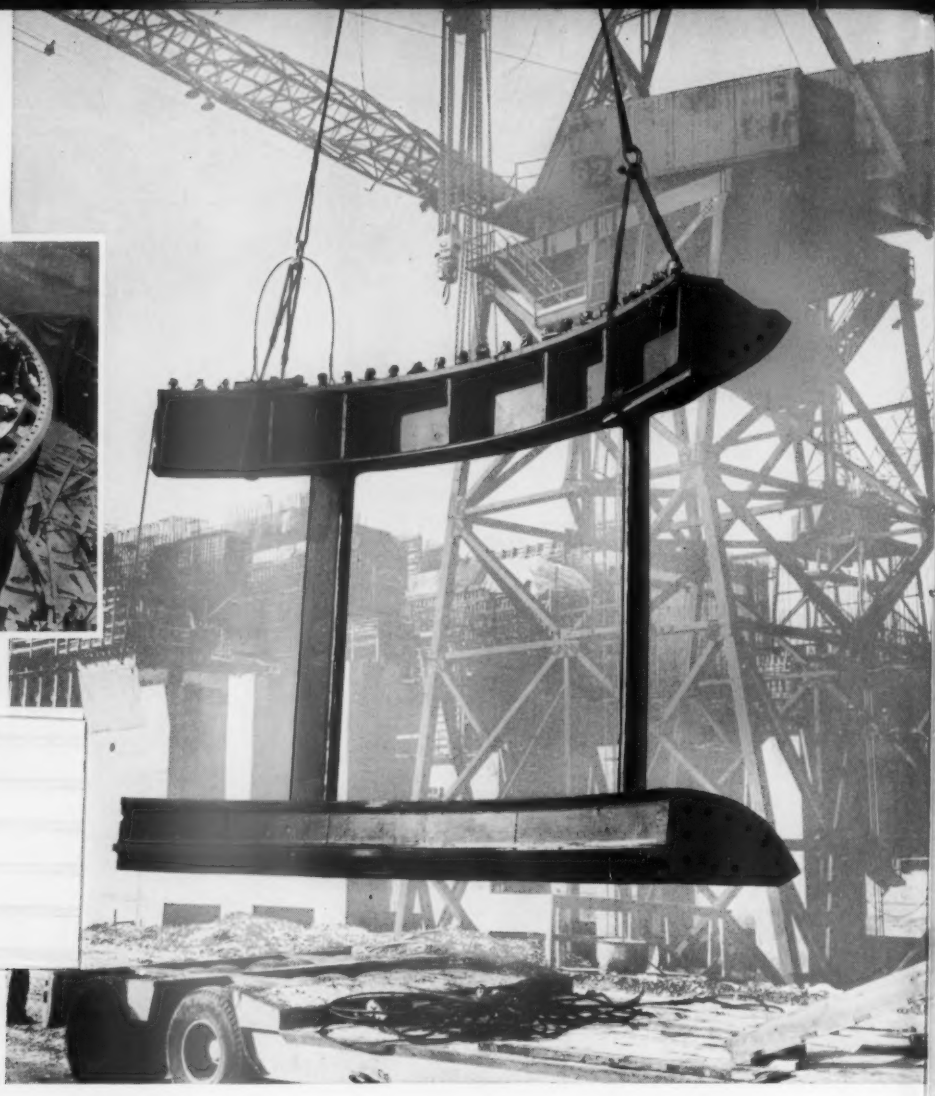


DESIGN ADVANCES IN TODAY'S GENERATORS... PAGE 20

(Right) Stay ring section of Allis-Chalmers turbine being lifted into place during field assembly at Barnhart Island powerhouse site. (Below) Completed stay ring assembly being leveled. The whole project will consist of 16 turbine units on the American side and 16 on the Canadian side.



Photos courtesy of Power Authority of the State of New York, Uhl, Hall and Rich, Engineers.



St. Lawrence Power . . . Near Reality

A-C turbines to tap river . . . boost industrial expansion

IN goes another Allis-Chalmers hydraulic turbine to help harness the waters of the mighty St. Lawrence River.

The breath-taking St. Lawrence power and seaway project, realizing a 50-year dream of two great nations, will soon amplify shipping lanes to the Great Lakes and provide an additional two million kw of much needed power.

The Barnhart Island powerhouse will include eight Allis-Chalmers hydraulic turbines and cabinet-type governors for all units on the United States side of the river.

Each of the A-C fixed-blade propeller-type turbines will develop 85,000 hp. Their cast steel runners are 20 feet in diameter; forged steel main shafts are over 3 feet in diameter.

World-recognized shop facilities and unsurpassed engineering experience in designing and building large hydroelectric units are reasons why Allis-Chalmers can be selected with confidence. The engineering experience connected with over 16 million installed hydraulic turbine horsepower can be yours. Call the Allis-Chalmers representative near you, or write Allis-Chalmers, Power Equipment Division, Milwaukee 1, Wisconsin.

A-C ALLIS-CHALMERS

ALLIS-CHALMERS

A-5420

ALLIS-CHALMERS Electrical REVIEW

THE COVER

GIANT 1800-rpm rotor of 300-mw turbine-generator unit is one of the first to be tested in new high retention test pit at Allis-Chalmers West Allis Works. A short article on page 14 describes outstanding features of the facility.

Allis-Chalmers Staff Photo by Harold Shrode and J. E. Gosseck

Allis-Chalmers

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Vol. XXII No. 2

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INDUCTION MOTOR TORQUES DEFINED

by R. C. MOORE
Motor & Generator Dept.
Allis-Chalmers Mfg. Co.

TORQUE CHARACTERISTICS of 400-hp, 2300 - volt, 720 - rpm, weather - protected squirrel-cage motor are carefully matched to the induced draft fan characteristics.

Terms describing induction motor torques are often confused. Here is an article aimed at ending this confusion.

WHEN SPECIFYING A MOTOR, describing its load requirements or selecting the type to be used, there are several torque requirements that should be made clear. Proper application of induction motors insures sufficient torque under all operating conditions.

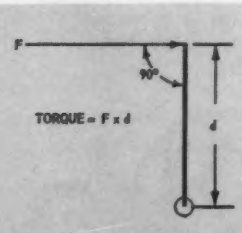
Torque is a turning moment such as that required to turn the crank on a pencil sharpener, an old coffee grinder or an engine. In Figure 1, torque is the product of the force *F* times the distance *d*. If force *F* is at some other angle than 90 degrees, as shown in Figure 2*a*, then torque is the force *F* times the perpendicular distance d^1, or the force component at 90 degrees times the crank length *d*, as shown in Figure 2*b*. Likewise, if the crank arm is crooked, as in Figure 2*c*, the torque is force *F* times the perpendicular distance shown by the dotted line.

As might be expected, the unit of torque would involve ounces, pounds, grams, or some appropriate similar unit describing the force *F*, along with inches, feet, centimeters, or some units of length describing the distance *d*. Since energy units are designated in foot-pounds, and so forth, the torque units in this country are commonly expressed in ounces-inches (oz-in.), pounds-feet (lb-ft), and so forth.

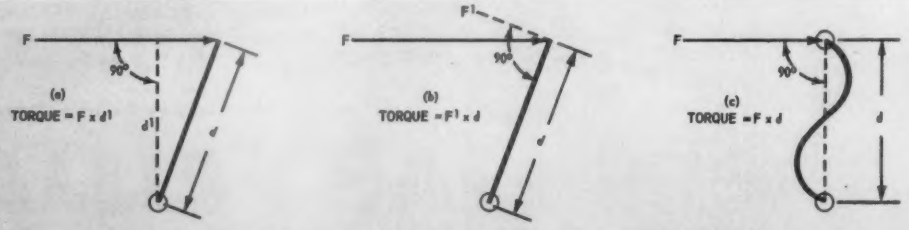
Other methods of expressing torque are sometimes used; however, they are not usually found in specifications.

Kinds of torque are numerous

Since a twisting or turning effort, that is, torque, can exist whether a motor is running or not, it might be expected that there are many types of torques. Friction torque, for example, will apply to the torque of the bearings tending to resist the movement of a rotor from standstill. Similarly, the motor windage at full speed imposes a resisting effort on the rotating parts, and a torque due to windage develops. Another example is the pulsating torque of a reciprocating compressor which produces torque reactions in the driving motor. The reactions developed in the motor are called damping torques. Induction motors may also



TORQUE of crank is turning moment. **(FIG. 1)**



PRODUCT of force times distance is expressed in lb-ft, oz-in., etc. **(FIG. 2)**

have synchronous torques, and synchronous machines may have induction motor torques.

Although there may be many types of motor torques found in motor theory and design, there are but a few important types encountered in specifications or applications. These few types are important enough to merit special consideration. In fact, many of them have been standardized and given standard definitions.

Full-load torque is basic value

Frequently, torques are expressed in percent. To obtain values in pounds-feet, or some other similar units, the percentage must be multiplied by a basic or normal torque value. This basic or normal torque, considered 100 percent, is the motor full-load torque determined from the following equation:

$$T = \text{torque in lb-ft} = \frac{\text{hp} \times 5252}{\text{rpm}}$$

where hp is rated full-load horsepower and rpm is full-load revolutions per minute.

Example: An 800-hp, 1190-rpm motor has a full-load torque of

$$T = \frac{800 \times 5252}{1190} = 3530 \text{ lb-ft (pounds-feet)}$$

If the torque of the motor at standstill is 120 percent, the torque value in lb-ft is 3530 × 1.2 or 4236 lb-ft.

The torques which occur most frequently in commercial design, specifications, and applications are:

(a) Breakdown Torque

(b) Pull-Up Torque

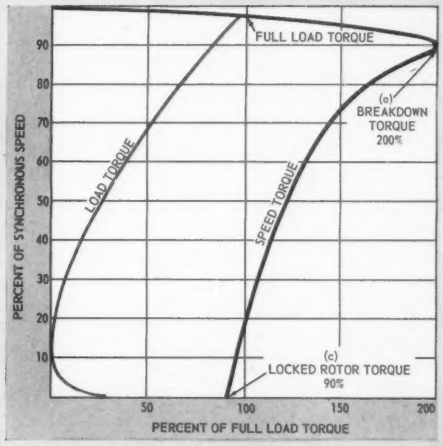
(c) Locked-Rotor Torque

These torques, along with rated full-load torque, define important points, shown respectively as *a, b,* and *c* on the motor speed-torque curves in Figures 3 and 4. The speed-torque curves show the torque which an induction motor of typical design might develop at full voltage for speeds from standstill to top speed. The dissimilarity in the shape of the torque curves is due to motor design differences. A comment on the influence of motor speed-torque curves is valuable before discussing the three torque points.

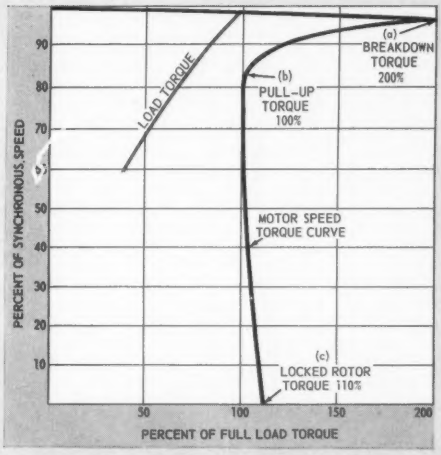
The importance of the motor speed-torque curves and the torque points indicated on them is made clearer when the torque curves of the driven machine are also plotted in the figures. The torque difference between the motor torque curve and the load curve is the net torque which will bring the combined unit up to speed. Should this difference in torque become zero at any speed during the acceleration of the motor with its load, then there will be no further increase in speed and full speed will not be reached. In the case of the curves of Figures 3 and 4, the torque difference between the curves indicates that the units have sufficient torque to accelerate to full speed.

Torques evaluated

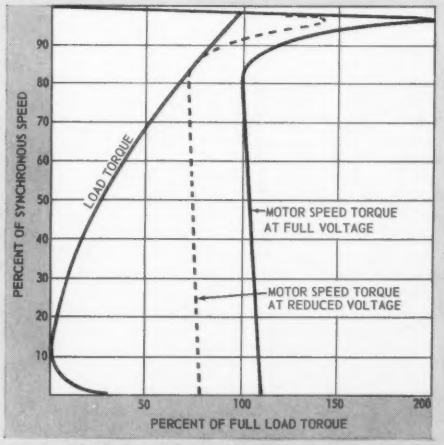
The specific importance of any of the three torques can now be discussed in detail, if we refer to Figure 5, which is the same as Figure 4 except for the added dashed line curve. The dashed line curve shows the motor torque with an assumed reduced voltage at the motor terminals.



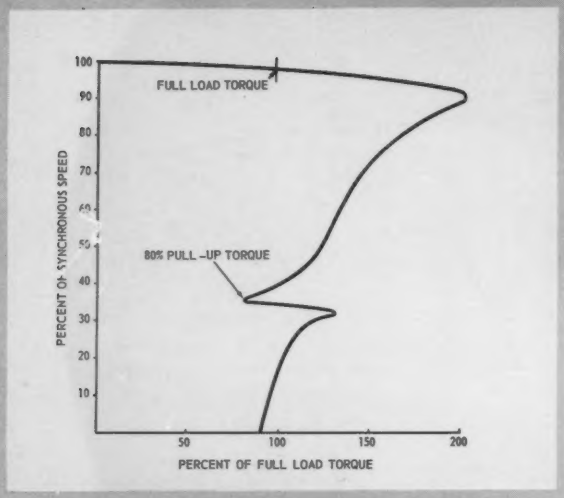
MOTOR torque characteristics are built into motors to suit their applications. **(FIG. 3)**


(a) BREAKDOWN TORQUE 200%
(b) PULL-UP TORQUE 100%
LOAD TORQUE
MOTOR SPEED TORQUE CURVE
(c) LOCKED ROTOR TORQUE 110%
PERCENT OF SYNCHRONOUS SPEED
PERCENT OF FULL LOAD TORQUE

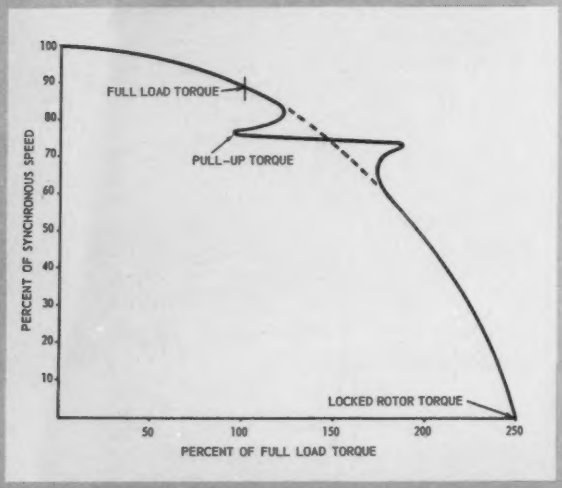
PULL-UP TORQUE is more pronounced in some designs than in others. **(FIGURE 4)**


LOAD TORQUE
MOTOR SPEED TORQUE AT FULL VOLTAGE
MOTOR SPEED TORQUE AT REDUCED VOLTAGE
PERCENT OF SYNCHRONOUS SPEED
PERCENT OF FULL LOAD TORQUE

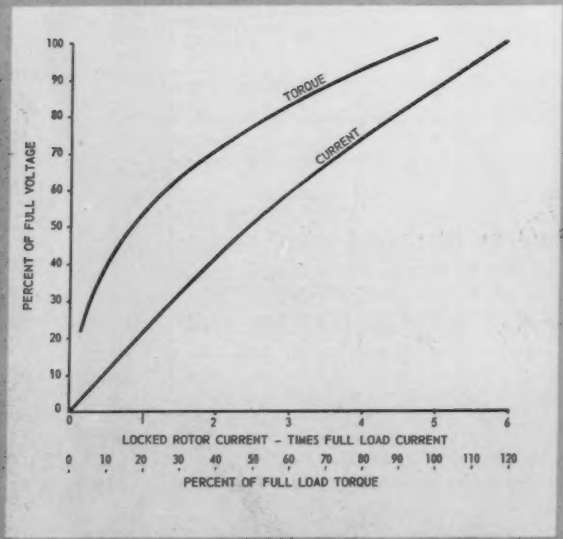
MOTORS will stall if their torque curve shifts too far with reduced voltage. **(FIG. 5)**



CUSPS in induction motor torque curves do exist in poor designs or damaged motors. **(FIG. 6)**



DEFINITE pull-up or breakdown torque points are not as obvious with some motor designs. **(FIG. 7)**



RULE that locked-rotor torque varies with the square of the current is good to remember. **(FIG. 8)**

Breakdown torque is important, since it will determine whether the motor will continue to carry its load through voltage dips without danger of the unit stalling. The dashed curve of Figure 5 shows that the load torque is within the motor breakdown torque capability at reduced voltage. However, a further decrease in motor voltage could cause the load torque to exceed the motor torque and stalling would result. The torque at the breakdown point can be considered to vary as the square of the motor impressed voltage. For example, a motor having a specified value of 200 percent breakdown torque at full voltage would have only 100 percent torque at 70 percent voltage.

Pull-up torque. The minimum torque on the motor develops at standstill. In Figure 5 the dashed curve showing motor torque with reduced terminal voltage indicates that there will be sufficient torque at zero speed to break away the load from rest. If the motor terminal voltage were less than assumed for the dashed torque curve, the locked torque might be reduced to such a low value that the motor could not start. As an approximation, the assumption is often made that the torque at rest will vary as the square of the impressed voltage. Actually, the torque varies as the square of the current, and the current is usually not linear with voltage.

Starting difficulties may also arise with too low a voltage across the motor when reactor, autotransformer, or other type of reduced voltage is employed. Taps on the reduced-voltage starting equipment provide means of increasing the motor impressed voltage where necessary.

The voltage dips occurring when larger motors are thrown across the line might prevent motors from starting or reaching full speed. If a motor is carrying a load, the motor might not have sufficient torque to carry through voltage dips caused by other motors starting.

Standard definitions given

Certain induction motor torque characteristics occur frequently in theory, design, application, specifications, and technical articles. Over the years a terminology to describe these torques has developed among educators, designers, and others. Different terminology has arisen in the past to describe the same thing. There is always the danger of misunderstanding of terms or of shades of meaning when torques are not specifically defined. For example, what is now defined as breakdown torque in accepted standards has been referred to in the past by various other expressions, such as "maximum torque," "max. torque" and "pull-out torque." Shades of meaning can often arise to becloud the understanding of a particular term. For example, does locked-rotor torque refer to the average or minimum torque with respect to rotor position? The American Standards Association has defined in its standard "ASA C42-1941"[1] the following definitions for the three commonly used torques.

Breakdown torque

"The breakdown torque of a motor is the maximum torque which it will develop with rated voltage applied at rated frequency, without an abrupt drop in speed."

Prior to the adoption of this definition, the torque was frequently referred to as maximum torque, or simply as max. torque. However, since maximum torque may occur

at standstill, misunderstanding could exist if the definition was not further qualified by the idea of an abrupt drop in speed. The term breakdown torque includes both the idea of maximum torque and the abrupt drop in speed.

Occasionally, the term pull-out torque is used by some to mean breakdown torque. The usage is incorrect, since the term pull-out has a definite meaning, as defined in the standards, only when applied to synchronous machines.

Pull-up torque

"The pull-up torque of an alternating current motor is the minimum external torque developed by the motor during the period of acceleration from rest to the speed at which the breakdown torque occurs. For motors which do not have a definite breakdown torque, the pull-up torque is the minimum torque developed up to rated speed.

Speed-torque curves of induction motors are frequently of the type shown in Figure 3. There is no point on the curve which will satisfy the definition unless one can consider the locked-rotor and pull-up torques coincident at rest. In large motors and high speed motors of high efficiency, the shapes of some speed-torque curves are similar to the full-voltage curves shown in Figures 4 and 5. As applied to these curves, the term pull-up torque provides reference terminology for the minimum torque. General usage of the term pull-up torque appears to be relatively recent.

The shape of double-cage induction motor speed-torque curves is not too unlike the curves in Figures 4 and 5. Pull-up torque values can be identified on such curves.

It is also of interest to point out that deviations from the smooth motor torque of Figure 3 can exist. The deviations can be in the nature of cusps in the curve and may be the result of motors rewound for different speeds, coils cut out of windings, poor or damaged cage construction, etc. A torque curve with a cusp is shown in Figure 6. The minimum torque shown would fulfill the requirements of the definition for pull-up torque. A motor of good design, however, would not have the cusp shown in the torque curve, but for purposes of illustrating the meaning of pull-up torque the curve is shown with the cusp.

Reference is made in the definition of pull-up torque to motors which do not have a definite breakdown torque. Such a torque curve is shown in Figure 7. Again for illustration, if there would be cusps in the torque curve, the minimum torque would be the pull-up torque. With no cusps in the curve, a smooth curve shown by the dashed line bridging the cusp interval is obtained. The motor would then have no pull-up torque value.

Locked-rotor torque

"The locked-rotor torque of a motor is the minimum torque which it will develop at rest for all angular positions of the rotor, with rated voltage applied at rated frequency."

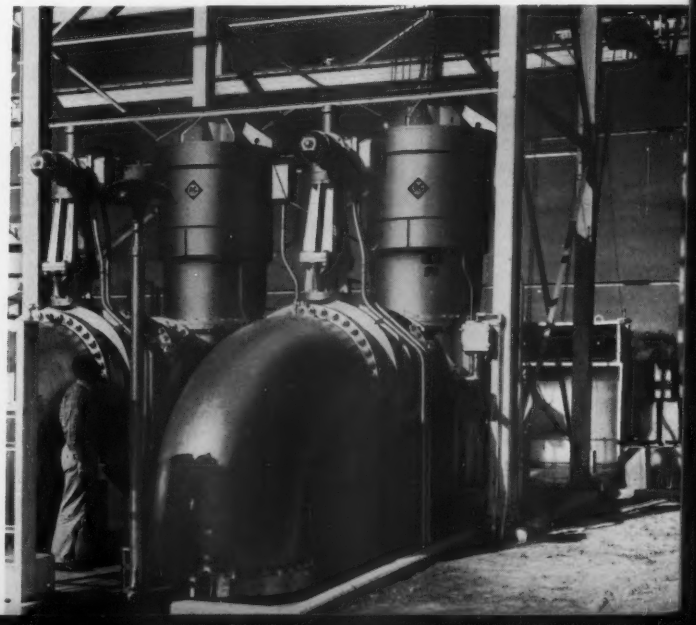
Other terms which have been used in the past are locked torque, breakaway torque and static torque. Static torque is still recognized as suitable terminology, although the term locked-rotor torque is generally preferred. In the definition the word "minimum" is significant, since there are frequently small variations in locked-rotor torque, depending on the angular position of the rotor with respect to the stator. In poorly designed or revamped motors, such as those reconnected or rewound for different speeds and those with coils cut out, the torque variations at rest may be considerable with rotor angular position. Situations have occurred in older machines when the motor refused to start because the rotor was in a position where the minimum torque was inadequate to start the unit.

In the locked or "at rest" condition, the torque will vary as the square of the current. As stated previously, the assumption is often made that the torque at rest varies as the square of the voltage. This assumption is not strictly correct because locked-rotor current is usually not linear with respect to voltage. The curve in Figure 8 shows locked-rotor current and voltage with a variation of torque as the square of the current.

Technical groups have long recognized the desirability of standardization and have defined the terminology most frequently used to describe machine characteristics. The use of this established terminology provides a firm basis to assure correct motor torque characteristics and proper motor application.

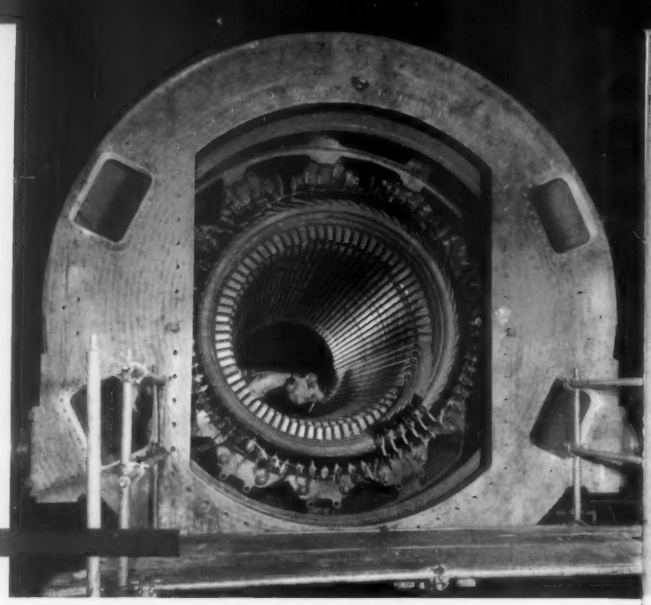
INDIVIDUAL wheel drives on stacker-conveyor represent a machine-type load. Motors rated 7½ hp, 1040 rpm have 275 percent locked-rotor torque (Design D) to break away their high inertia geared load.

PUMP LOADS require a different motor torque characteristic than high inertia fans or machine loads. The 250-hp weather-protected motors shown are driving circulating water pumps in a power station.



540-Degree Stator Coil Transposition

- **SOLVES EDDY-CURRENT PROBLEMS**
- **REDUCES HOT SPOT TEMPERATURES**



STATOR for 1800-rpm generator of 300-mw, 3600/1800-rpm steam turbine generator unit has new 540-degree coil transposition.

by W. L. RINGLAND
Chief Engineer
Motor and Generator Dept.
Allis-Chalmers Mfg. Co.

THE PROBLEM OF REDUCING EDDY CURRENTS is particularly severe in modern large turbine-generators because of the deep single-turn coils necessary to provide current-carrying capacity. The two principal types of eddy current problems are accentuated. First, because of the large total amperes per slot, the greater flux density through an individual strand near the top of the slot (nearest to the air gap) induces more voltage between the top and bottom faces of the strand, causing more eddy currents to circulate within the strand. The flux density across the slot is shown in Figure 1. Thinner strands provide a practical solution to this type of eddy current.

The second principal type of eddy current, and potentially much greater than the first, traverses the full length of some strands from one end of the coil side to the other, returning through other strands of the same coil side to complete the circuit. In an untransposed coil these eddy currents normally add to the load current and total loss in strands nearer to the air gap and subtract from the load current for the lower strands of the coil side. The effects are an increase in total loss and hot strands in the top of the coil, unless some corrective measures are taken. Voltage producing these eddy currents is induced by leakage flux across the slot and coil ends between the top and bottom strands. It is evident that greater amperes per slot, producing flux across a deeper coil side, will result in increased induced voltage differences and eddy currents between strands. Elimination of these eddy currents can be accomplished by transposing the strands in such a manner that there is no net difference in flux linking any pair of strands. In other words, the induced voltages in all strands are equal.

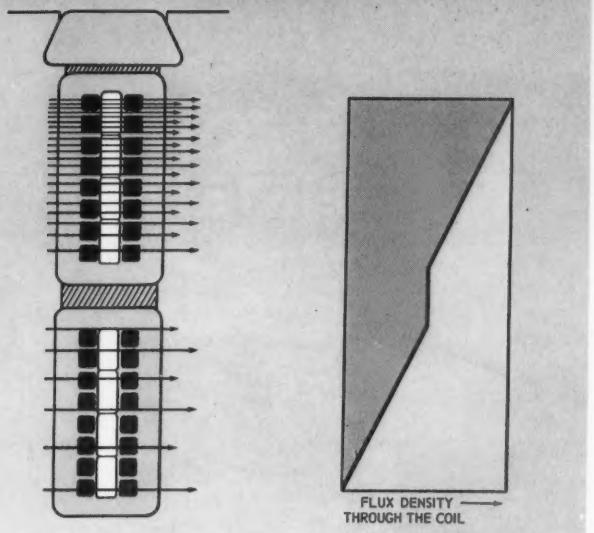
Old system is not complete solution

The 360-degree transposition, shown in Figure 2, is a perfect solution for eliminating only those eddy currents between strands resulting from flux across the slot part of the coil. The strands are uniformly rotated from one position to the next, so that each strand occupies all possible positions for equal distances, returning to its original position after having traversed the core length. Voltage differences between strands due to flux across the slot or within the core length are thus eliminated. The fact that the strand occupies all possible positions accounts for the 360-degree designation. Crossovers occur at the top and bottom of the coil side where each strand crosses over from one vertical layer to another in changing position.

Unfortunately, the 360-degree transposition offers no relief for voltages and eddy currents between strands caused by flux beyond the core. Since strand positions are the same at both ends of the core, induced voltages between top and bottom strands in the two ends are additive. On smaller machines the effects of end voltages may be negligible and normal 360-degree transposition is adequate. However, on larger machines, where eddy current effects are potentially more severe, the coil end voltages may cause large eddy currents and high temperatures in some strands unless they are counteracted.

End flux problem solved

The need for an effective means of substantially eliminating eddy currents between strands caused by end flux as well as slot flux has been satisfied by a new transposition in which the strands of a coil side are rotated in position one and one-half times, or 540 degrees, within the core length. This arrangement results in the strand positions at one end being reversed or turned over from their positions on the opposite end of the core. For example, a strand on top of the coil side at one end of the core reaches a position at the bottom of the coil side at the other end. Voltages induced between top and bottom strands by end fluxes at the two ends are, therefore, equal and opposite, and net voltage and eddy currents between the strands are eliminated. The effects of the small remaining voltages between



GREATER LEAKAGE FLUX through top coil side causes more eddy currents between strands than in the bottom coil side. **(FIGURE 1)**

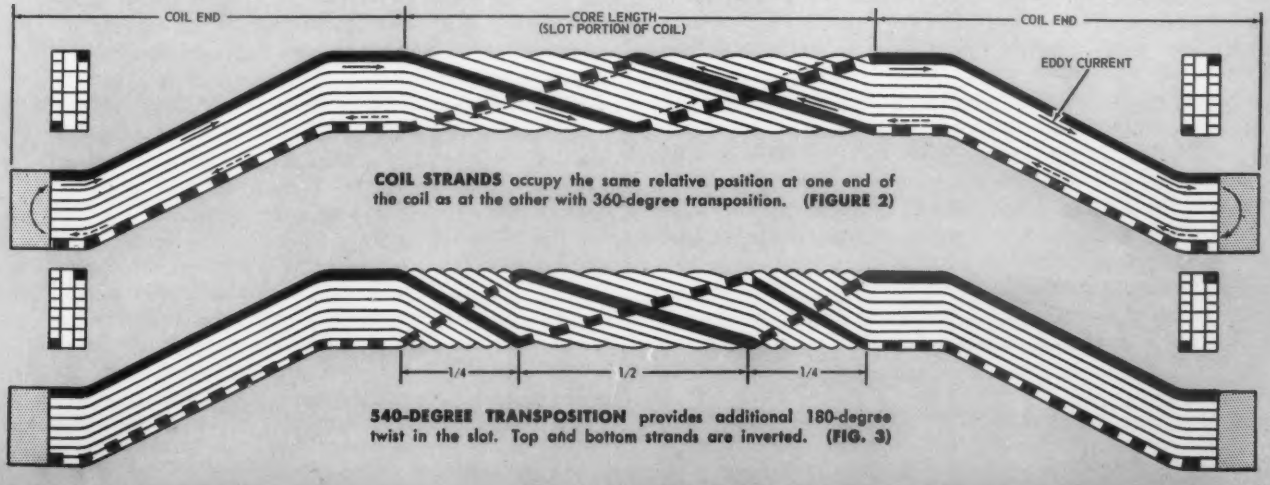
the middle and outer strands due to nonuniform flux distribution through the coil are negligible.

Effectiveness of the new 540-degree transposition against slot flux is ideal and equal to that of the 360-degree transposition only because of a special nonuniform distribution of the transposition crossovers. The first 180 degrees of transposition are uniformly distributed over the first quarter of the core length. The second 180 degrees of transposition are distributed over the middle half of the core length, resulting in twice the initial crossover spacing. The remaining 180 degrees of transposition are uniformly distributed over the remaining end quarter of the core length with the original close crossover spacing. Distribution and position of the strands in the two end quarters are identical. Therefore, the effects of the two end quarters are the same as distributing the first 180 degrees of a 360-degree transposition over half the core length. The middle half of the coil containing the remaining 180 degrees of transposition completes the ideal effect of a 360-degree transposition with respect to slot flux.

Advantages of the new 540-degree transposition over other known ways of reducing eddy currents between strands due to end flux have been proven by test and are inherent in the construction. One older method extended the 360-degree transposition beyond the slot into the coil ends, the number of crossovers in the ends being proportional to the calculated end flux. This method has two important defects. The amount of end flux is almost impossible to calculate with the precision necessary to determine an effective transposition. Furthermore, even though the best number and spacing of end transposition crossovers would be exactly determined, equalization of strand voltages is impossible because the phase angle of the induced strand voltages changes between the ends of the core and the extreme ends of the coils. Neither of these problems arises in the new 540-degree transposition because the end voltages are always equal and opposite at the two ends, cancelling each other regardless of their magnitude or phase angle relative to the voltage induced in the slot.

Another older transposition method against end effects divides the coil into groups of strands and transposes the position of each group in the coil through a number of coils equal to the number of groups. Thus a coil divided into four groups might have its top group connected to the second group in the next coil, and so on through the four coils, all groups changing positions at each coil. Since all groups occupy all possible positions in the coils, the voltage difference between groups is reduced. However, the voltage difference between groups cannot be cancelled out because the phase angle of the induced end voltage varies from one coil to the next. Furthermore, voltages between strands of each group are not eliminated. Perhaps the principal disadvantage of the group transposition, particularly in conductor-cooled machines, is the mechanical difficulty of transposing group positions at the coil connections, keeping the groups insulated from each other throughout the groups of coils corresponding to the group transposition pattern. Also, the usual 360-degree transposition is still necessary in all coil sides to eliminate the effects of slot flux.

Although there are 50 percent more crossovers to be made in the 540-degree transposition than in the 360-degree transposition, and spacing must be carefully controlled, the manufacturing techniques are familiar and the change to the new method requires the minimum of extra manufacturing difficulty. Once the strands are assembled, insulation, installation, and connection of coils follow normal procedures. The core length sufficient to accommodate the additional number of crossovers is normally available in most machines of 134 mva and above.



COIL STRANDS occupy the same relative position at one end of the coil as at the other with 360-degree transposition. **(FIGURE 2)**

540-DEGREE TRANSPOSITION provides additional 180-degree twist in the slot. Top and bottom strands are inverted. **(FIG. 3)**

EXCITRON RECTIFIERS

RECTIFIER ROOM in aluminum reduction plant has twenty-four 6000-amp, 750-volt dc pumped-type excitron rectifier assemblies, their control and dc switchgear.

by A. D. MILLIKIN
Rectifier Section
Allis-Chalmers Mfg. Co.

Proven principles and components go into new excitron rectifiers and control.

THE EXCITRON-TYPE MERCURY-ARC RECTIFIER, operating on the continuous excitation principle, has probably the longest history of any power-rectifier type in general use today. Through the years, designs have progressed from low capacity glass envelope tubes to large steel tank multiple-anode type, and finally to the sturdy, heavy duty, steel tank single-anode tubes of today.

While all mercury-arc rectifier tubes have the same general operating components, there are several design features of the excitron tube that are outstanding. Excitron rectifiers are divided into two general types: pumped and sealed. Both types have their place in our expanding economy. Except for the methods of sealing, the internal construction of the sealed-type tube is the same as the time proven pump type. A cross-section view of a pumped tube is shown in Figure 1.

The excitron tube employs an internal cooling coil to carry away approximately 92 to 95 percent of the internal heat loss. Since the coil is located entirely within the vacuum vessel and extends for nearly the full length of the arc working chamber, the surface area for condensing the mercury vapor is more than double that available with an external cooling jacket. This feature allows excellent control of vapor pressure over a wide range of loads.

The internal cooling coil is insulated from the outer tank at its plate inlet by vacuum-tight insulating bushings and by an insulating quartz ring at the cathode. With this construction the arc working area is completely surrounded by an insulated shield, and the possibility of arc travel to the tank walls is practically eliminated.

Insulating supports for the other tube elements are located outside the arcing space and are therefore shielded in such a manner as to greatly reduce metallization of these parts. Tube life is thereby greatly increased.

Teflon gaskets seal pumped units

The pumped-type tube employs Teflon gaskets for all vacuum seals except the main anode inlet seal, which is of vitreous enamel. Teflon has proven itself an excellent gasket material for vacuum seals. With these seals tube leakage rates of as little as 0.02 micron per hour are often obtained for final leakage tests after factory degassing. All vacuum joints are made directly between the two parts to be joined, without resorting to welded flanges or other components. This has greatly reduced the need for vacuum-tight welding techniques and expensive pressure tests in both the factory and the field.

While the sealed-type tube, shown in Figure 2, employs a general internal design identical to that of the pumped tube, they differ in the type of seals employed and the metals utilized for certain components. The cooling coil of the sealed tube is made of stainless steel to prevent corrosion and the penetration of hydrogen from the cooling water as a result of corrosion. Vitreous enamel seals of a laminated or sandwich construction are used for all inlet seals of the sealed-type tube. The main anode plate is welded vacuum tight to the tank proper, and no gasketing material is used at any point in the sealed-tube design.

The greatest difference between the pumped and sealed tube is the method of processing. The pumped tube is degassed by passing current from a low voltage source through the tube and driving out the internal gases by the heat generated from the arc losses. This method produces a wide heat gradient between the various internal parts: the anode becomes the hottest part, while the cooling coil and tank remain at or near the cooling water temperature. As a result of this wide temperature differ-

ence, the cooler parts are incompletely degassed and will continue to emit gases very slowly over a long period of time. The rate of gas discharge is not troublesome in the pumped tube due to the continual evacuation by the vacuum pumping system.

Sealed-tube vacuum process is involved

The sealed tube, which must operate without the benefit of continual pumping equipment, is degassed by an entirely different process. The tube is placed in a vacuum furnace and heated throughout by external heating elements to a temperature in excess of that attained by the hottest part during normal operation. The enamel bushings are heated to a temperature lower than the other components but still in excess of any temperature reached in service. After degassing is complete, the tube-evacuating pipe is closed off by a fusion welding process.

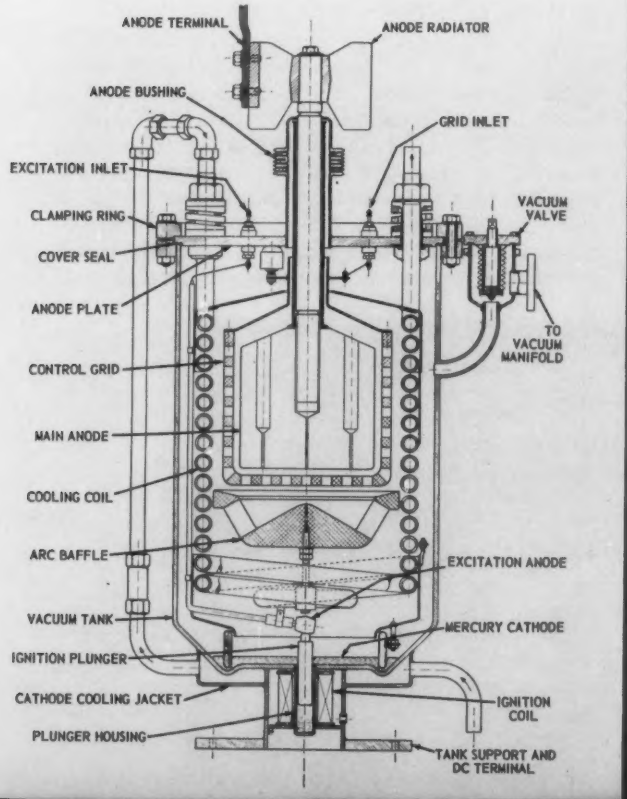
The operation of any mercury-arc rectifiers depends on an electron-emitting spot being present on the mercury pool (the cathode) at the time when the anode is at a positive potential with respect to the cathode. The excitron-type rectifier operates with a cathode spot maintained continuously. This tube is therefore continuously excited, hence the name excitron.

To maintain the cathode spot, a small auxiliary anode is placed in the lower region of the tube and energized from a direct current source. Small metallic-type rectifiers are used to supply a current of 7.0 to 8.0 amperes at the arc-drop voltage of 10-14 volts. An adjustable air-gap reactor is used on the alternating current side of the small rectifier to provide current adjustment. The open-circuit output voltage of this rectifier is roughly 45 volts. It provides a sufficiently high recovery voltage to produce arc stability over a range of arc drop. A simplified excitation circuit is shown in Figure 3.

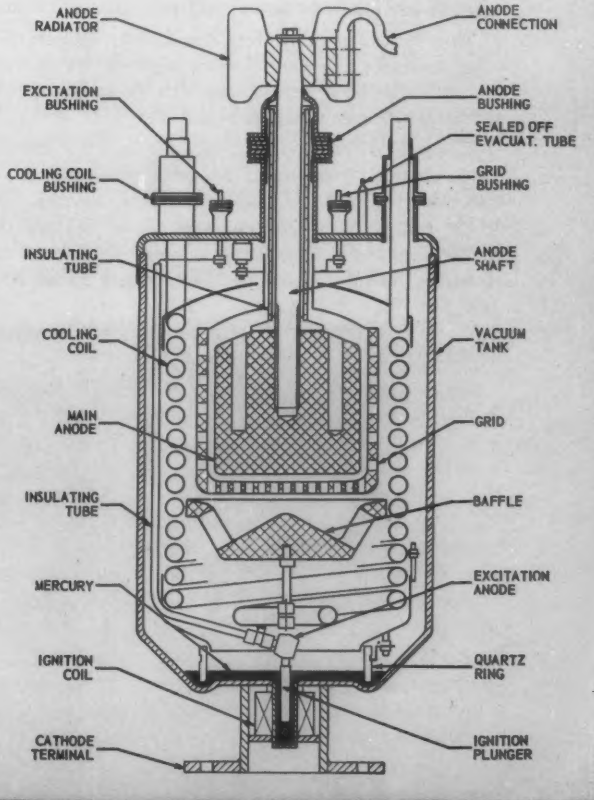
Arc is automatically reignited

To initiate the arc, a small steel plunger is housed in a nonmagnetic well which is welded to the bottom of the tank. An external coil around this well pulls the plunger below the mercury surface. When de-energized, the plunger will rise due to its natural buoyancy in mercury, and the tip will make contact with the auxiliary (excitation) anode. The coil and excitation anode are connected in series with the positive terminal of the excitation rectifier, and the cathode is connected to the negative terminal. When the plunger makes contact with the excitation anode, current is drawn, the coil is energized and the plunger is pulled below the mercury surface. As the plunger pulls away from the anode, an arc is established which is transferred to the mercury surface as the plunger submerges. So long as an arc is maintained, current flows and the plunger is held down. If the arc is interrupted, the plunger rises and reignites the excitation arc automatically, without depending upon any external relays or control devices. Protection against prolonged operation without excitation on one or more tubes is provided by a timing circuit initiated by current relays placed in each tube excitation circuit for this purpose.

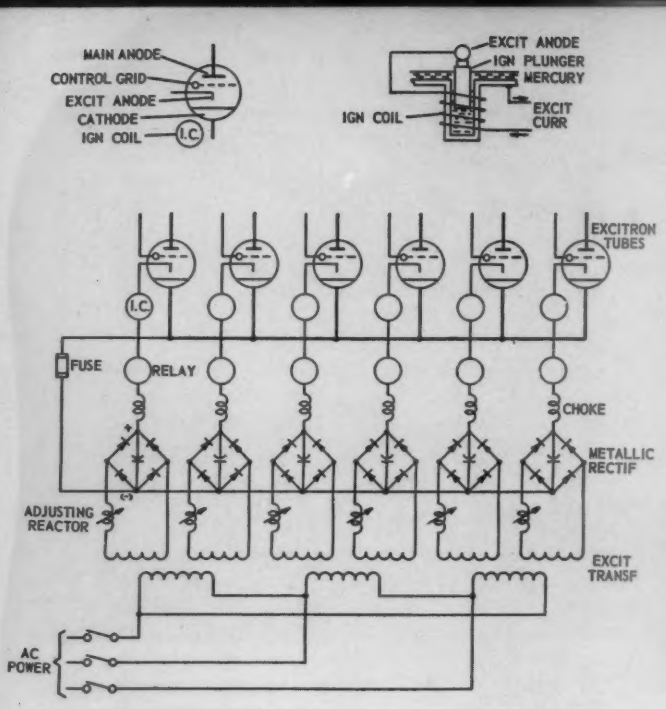
The output of the excitron rectifier is controlled by means of a grid which surrounds the anode. When a negative potential, with respect to the cathode, is placed on the grid, the anode is prevented from carrying current, although it becomes positive with respect to the cathode.



PUMPED-TYPE EXCITRON RECTIFIER TUBE, successfully used for many years, employs Teflon seal gaskets for the cover and all inlet and vacuum connections. **(FIG. 1)**



SEALED-TYPE EXCITRON RECTIFIER TUBE has same general construction as the pumped type, but cover has vacuum-tight weld and seals are of permanent vitreous enamel. **(FIG. 2)**



EXCITATION ANODE dc supply requires only simple circuit components. Reignition device is sealed within the tube. **(FIGURE 3)**

PUMPED RECTIFIER with its control and auxiliary equipment may be enclosed in completely factory-assembled unit. **(FIGURE 5)**

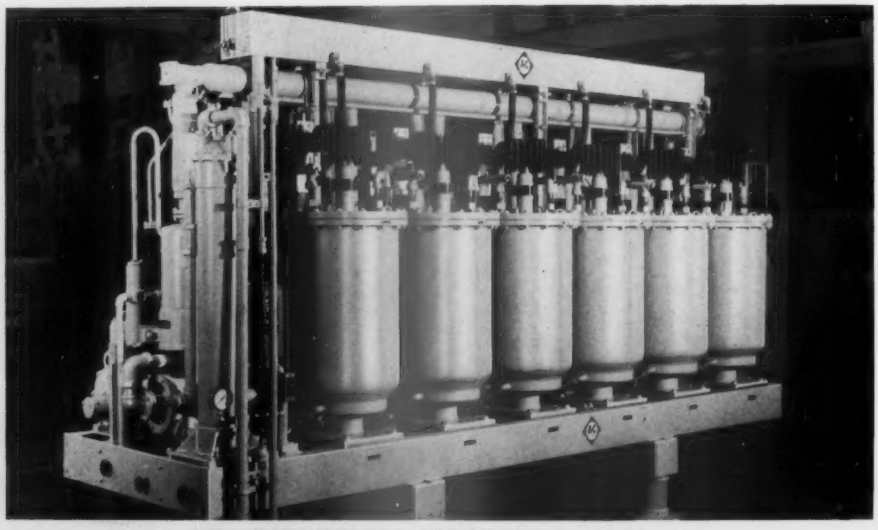
If the grid is made positive at any time during the anode's positive interval, the main arc will be established and current conduction will occur between anode and cathode. Once conduction is initiated, the grid has no further control over the anode until the end of the conduction period and after de-ionization has taken place in the vicinity of the main anode. The grid therefore offers not only a simple method of rectifier output control but a means of control having a low power requirement.

In addition to controlling the rectifier output, the grid also decreases the de-ionization time at the end of the anode conduction period and aids in reduction of arc-backs at the commutation point.

Control of the grid potential for excitron rectifiers is now obtained from specially designed saturable reactor circuits composed of trouble-free static devices. Due to their transformer-type windings, these devices offer a convenient and safe means of isolating the control circuits from the rectifier potential. The reactors are so designed that a change in control current of only a few milliamperes is required to produce a relatively large change in rectifier output. The low control current requirement has simplified the design of fast, accurate static-type regulators for both voltage and current control.

A voltage regulator, commonly used with the excitron today, may be considered as two circuits: one to sense the change in rectifier output voltage, and the other to amplify the change and provide control of the grid circuit.

The sensing element is a resistance bridge having ordinary resistance in two branches and nonlinear resistance in the other two branches. The nonlinear elements consist of ordinary incandescent lamps operated at approximately one-fourth their rated voltage. The bridge is connected across the rectifier output voltage in series with a suitable adjustable resistor, smoothing chokes and a rheostat so that a voltage of 120 to 150 volts is normally applied across the bridge. The regulator balances the bridge, maintaining constant current through the bridge at all



OPEN FRAME RECTIFIER ASSEMBLY of pumped rectifiers is usually preferred for large dc power supplies. **(FIGURE 4)**

times. The rectifier voltage level is set by means of a rheostat in series with the bridge. The normal output of the bridge in the controlling range is less than one volt.

Transistor amplifiers used

The voltage appearing across the sensing bridge is fed to a two-stage direct-coupled amplifier consisting of *p-n-p* type transistors.[1] Through this amplifier the output from the bridge is amplified approximately 100 times and fed into the magnetizing windings of the saturable reactor in the grid circuit to control the rectifier output.

The excitron rectifier is available in several types of assemblies covering the voltage range of 250 to 1000 volts dc and all standard kilowatt capacities. The assemblies may be either of the enclosed or open-package type construction and consist of either pumped or sealed-type tubes. Figure 4 shows a typical pumped-type unit, and Figure 5 an enclosed-type assembly of pumped tubes. A sealed-tube type enclosed rectifier is shown in Figure 6.

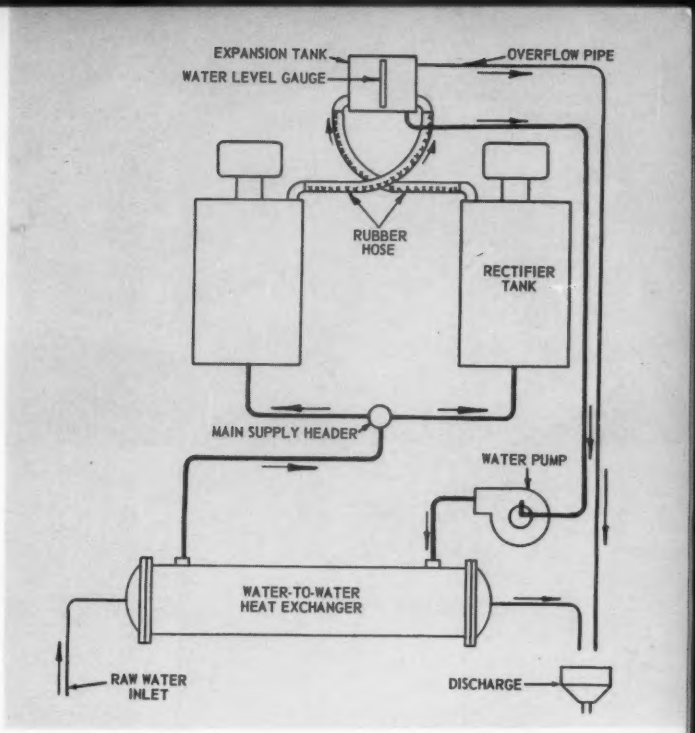
Each rectifier assembly consists of excitron tubes, in groups of six, twelve or more, mounted on a common frame with the required cooling equipment and vacuum pumps (for pumped-type tubes). The frame is integral with the cathode and is insulated from ground regardless of the type of assembly. The outer frame of the enclosed-type assembly and the control section or cubicle for all assemblies are grounded directly or through a ground fault protective system.

The closed circuit cooling system is normally kept at the rectifier potential. This arrangement eliminates the possibility of electrolytic current flow between the tubes and the cooling equipment. Any electrolytic action which might occur is concentrated on the raw water side of the cooling system, where it is more easily controlled. The raw cooling water is supplied through a length of rubber hose or insulating pipe. When required, electrolytic targets are located on the rectifier assembly. The cooling water discharge is through a section of insulating pipe with free discharge to an open drain.

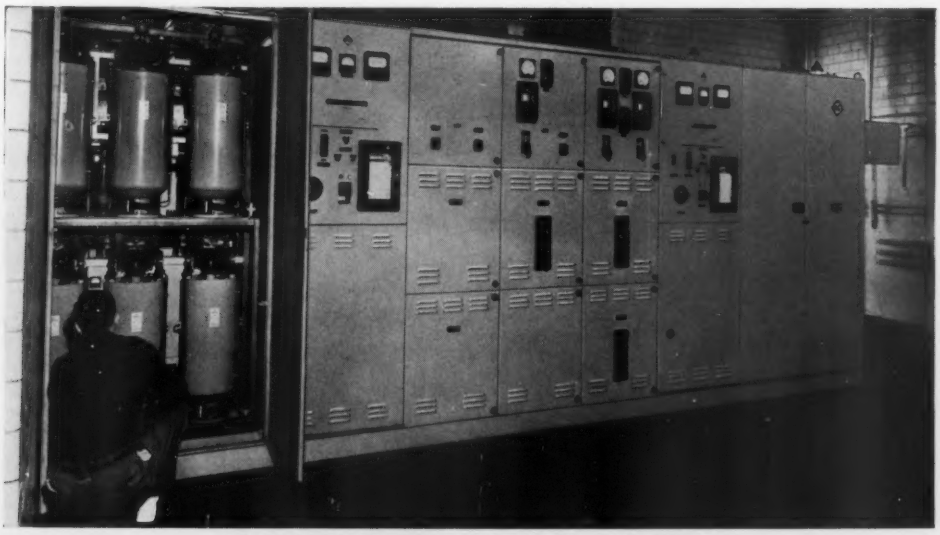
The tube-cooling circuit is completely isolated from the raw water circuit by the heat exchanger and therefore is easily treated against corrosion. The cooling principle is shown in Figure 7. Temperature expansion and liquid loss are handled by a large expansion tank vented to atmospheric pressure. The expansion tank acts as the return water header and offers a simple solution to the problem of eliminating entrapped air from the system. The tank also solves the more serious problem of water loss resulting from auxiliary power failure on a heavily loaded machine. Factory tests and field experience have shown no appreciable water loss due to failure of the auxiliary power supply of a hot machine, and no delay of service after the restoration of power. Natural circulation of the water, with the pump inoperative, prevents extreme overheating or damage to the tubes.

With the improvements and wide variety of designs offered by the excitron rectifier, industry has at its disposal a versatile tool to meet any requirement for electrical power conversion equipment.

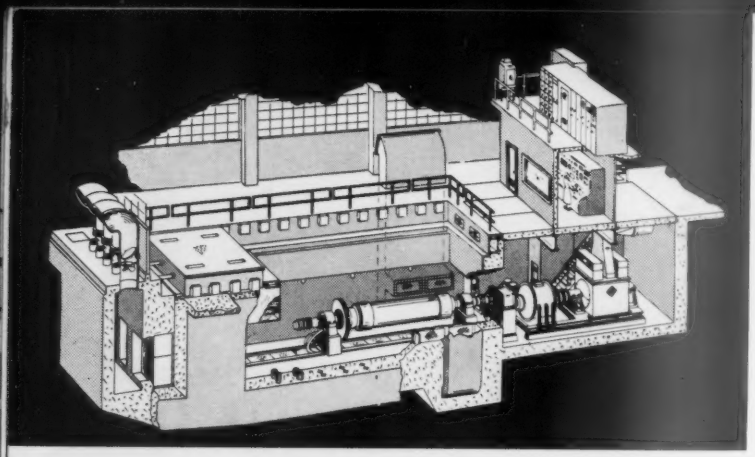
[1] "Transistors in Mercury-Arc Rectifier Control," John B. Rice, Allis-Chalmers *Electrical Review*, 2nd Quarter, 1957, p. 16.



EXPANSION TANK serving as return header eliminates entrapped air and minimizes water loss if auxiliary power fails. **(FIGURE 7)**



SEALED-TYPE RECTIFIERS are generally preferred for dc load-center substations like this 500-kw, 250-volt supply. **(FIG. 6)**



New High Energy Retention Pit

Permits Rotor Balancing and Overspeed Tests

UNDER SIMULATED OPERATING CONDITIONS

by **J. A. ZIMMERMAN**
Steam Turbine Dept.
Allis-Chalmers Mfg. Co.

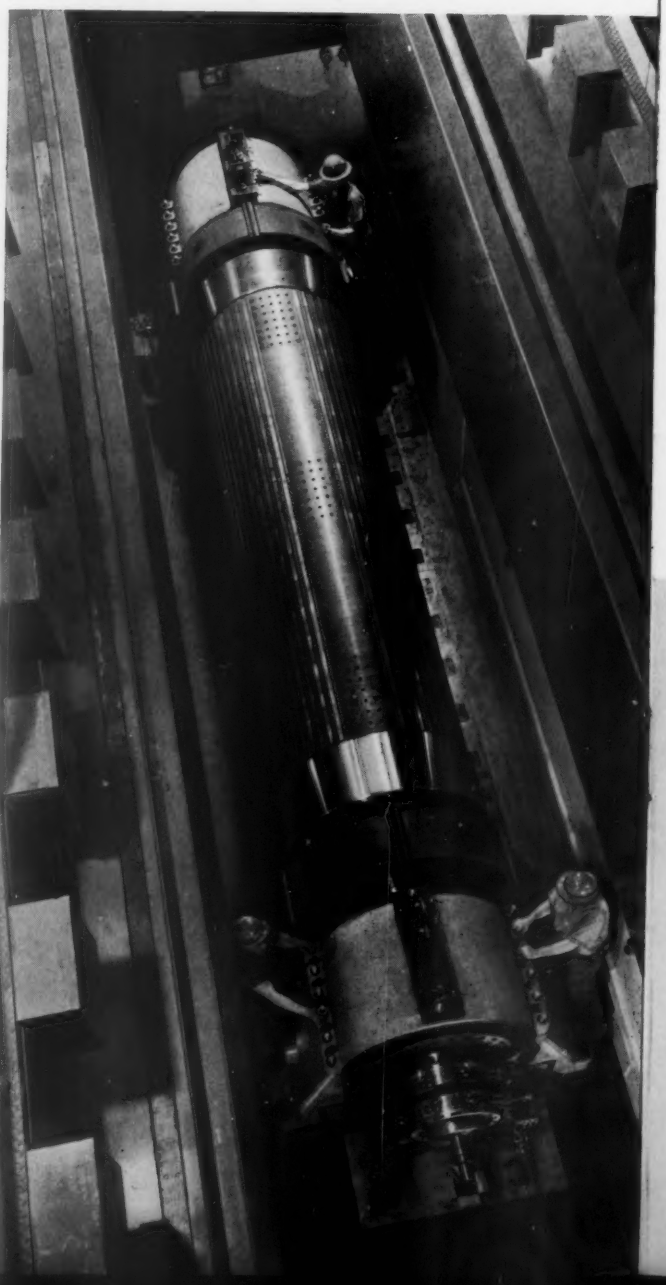
AS GENERATORS BECOME LARGER and larger, balancing and overspeed testing of their rotors become more and more critical. To facilitate precision balancing and accurate testing, a new test pit was built at West Allis Works.

Basic features of the pit are accurate speed control over the full generator speed and overspeed range. Convenience of operation and ease of installing rotors in the test setup make this facility a valuable plant addition. Objectionable noise associated with high speed balancing and testing is confined to the pit.

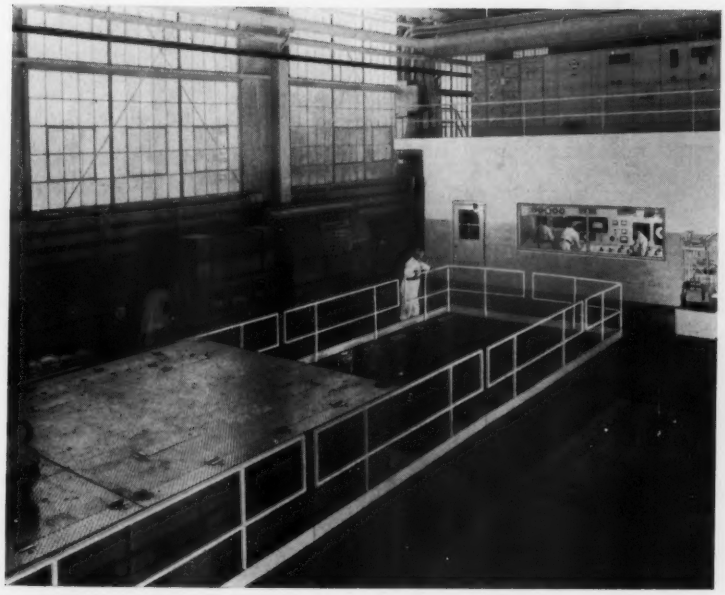
The control room, located on the main floor overlooking the pit, is complete with precision instrumentation for observation and supervision of the facility. Quick access to the generator rotor between runs is afforded by an elevator between the control room and the pit level. Rotor ambient temperature is regulated by control of four 20,000 cfm ventilating fans. Temperatures may be varied from room temperature to 100 C. Heat from bearings is removed by circulating oil through the bearings. The rotor cooling fans on larger rotors are covered during tests to reduce drive horsepower requirements.

Supplying power to the facility are six high voltage switchgear units and one 2400/480-volt dry-type 225-kva load center substation for auxiliary power. This equipment is conveniently located above the control room.

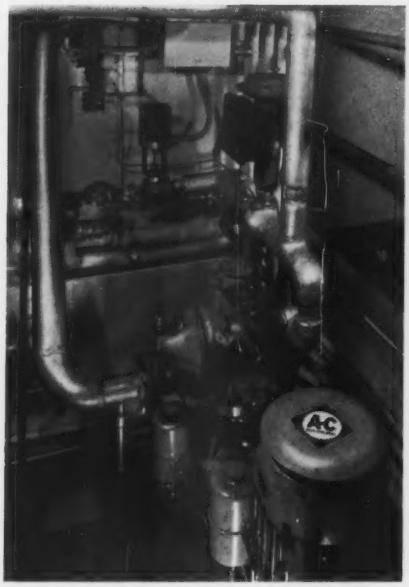
The 50-foot long, 11-foot wide and 18-foot deep test pit and its auxiliary equipment are shown in various views of the facility.



GIANT rotor being readied for test. These tests include balancing at various speeds and temperatures up through normal operating speeds and temperatures, and an overspeed test at 120 percent of rated speed.



PIT SECTIONAL COVERS are built of high retention construction with steel and timber 9 feet thick. The covers, which are removed while rotors are lowered into the pit, have breech block locking arrangement.

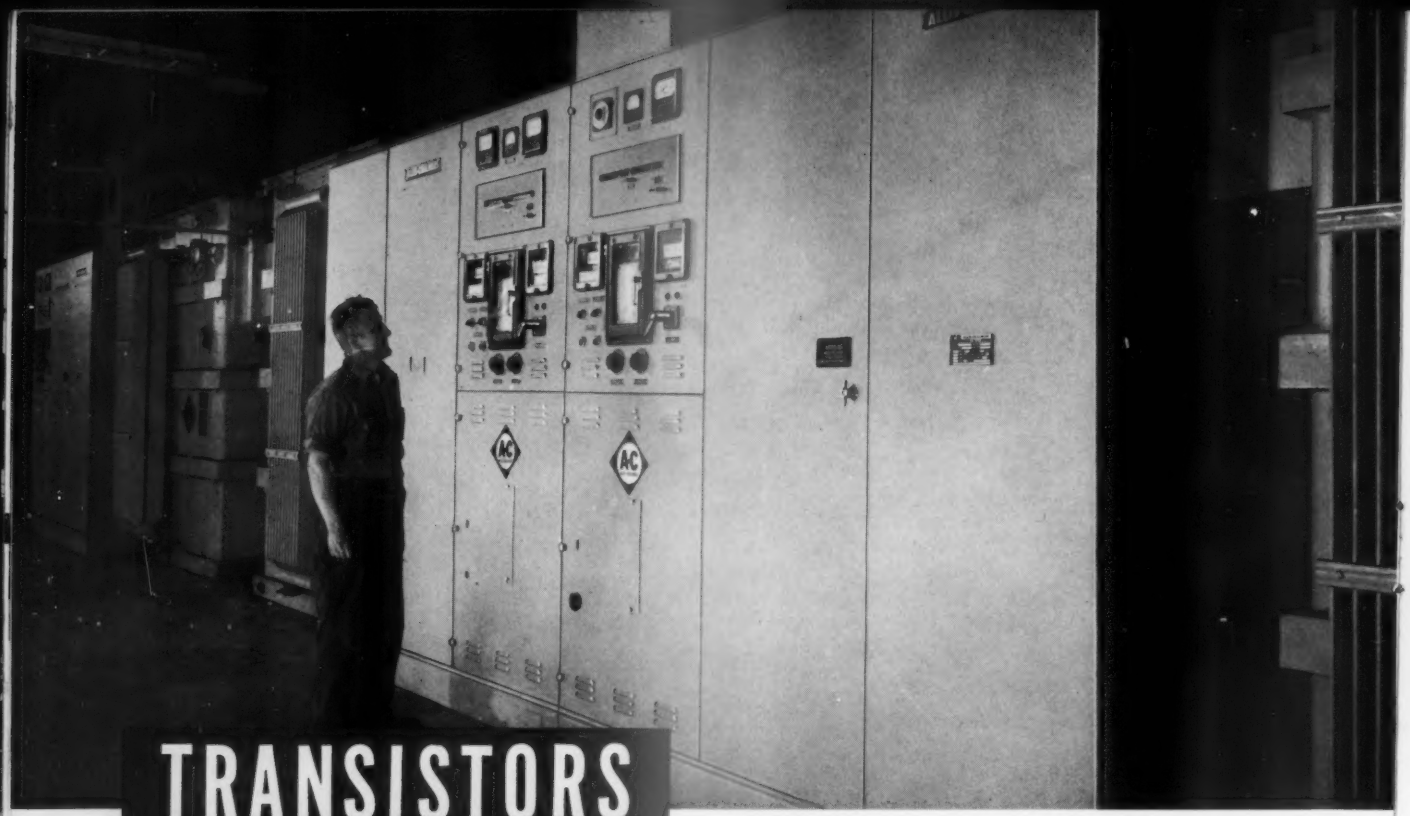


ADEQUATE SUPPLY of cool, clean oil is assured for pedestal bearings while rotor is being tested. Pressure system also supplies lubricating oil necessary for speed increasers and drive equipment.

ROTOR WEIGHING 98 TONS is shown being lowered into the pit. Pit size is more than adequate to handle the largest rotors now being contemplated. Rotor is for 300-mw turbine-generator unit.

CONTROL ROOM OPERATOR has complete control of entire test procedure. He has accurate indication of speed, vibration, and temperature of test rotor plus indication of drive equipment operation.

TWO-SPEED wound-rotor induction motor rated 2500 hp drives rotor on test through eddy-current coupling and speed increaser, providing accurate speed control as well as rapid acceleration and deceleration.



TRANSISTORS for Mercury-Arc Rectifier Control

TRANSISTORS control the current output of six rectifier units supplying 1500 amps each at 250 volts for producing chlorine electrolytically. The chlorine is used to bleach pulp in a paper plant in Maine. Shown are three of the complete dc substations. **(FIGURE 1)**

by JOHN B. RICE
Rectifier Section
Allis-Chalmers Mfg. Co.

Transistorized control of power rectifiers is answer for the most critical manufacturing processes.

RELIABILITY IS A MUST for large mercury-arc rectifiers used for supplying electrochemical loads such as aluminum pot lines, chlorine cell lines, as well as for battery charging or supplying other heavy industrial loads. Unscheduled shutdowns are extremely costly, both from the standpoint of loss in production and of possible damage to the process equipment. When automatic voltage or current regulators are required, the regulating equipment should be as reliable as the mercury-arc rectifiers they control. Mechanical regulators, used extensively in the past, are not considered sufficiently reliable for many of today's applications. Furthermore, mechanical regulators are not as accurate as the magnetic amplifier regulators developed in recent years. Being completely static, magnetic amplifier regulators are extremely reliable and can be designed to obtain the desired degree of accuracy. However, their cost is sometimes a factor in smaller installations, and they usually occupy more space than mechanical regulators.

Power transistors have been applied as the amplifying element of voltage and current regulators in several medium and large mercury-arc rectifier installations in the past two years. These transistor regulators possess the advantages of the magnetic amplifier type with regard to reliability and accuracy, but occupy much less space than an equivalent magnetic amplifier regulator. Furthermore, transistors have no inherent time delay. This characteristic decreases the likelihood of instability because the system has less need for damping. It also means that the regulator can be made as fast as other components of the regulator and the mercury-arc grid control circuit will permit.

Figure 1 shows part of a mercury-arc rectifier installation employing transistorized current regulators for regulating the current output for electrolytic production of chlorine.

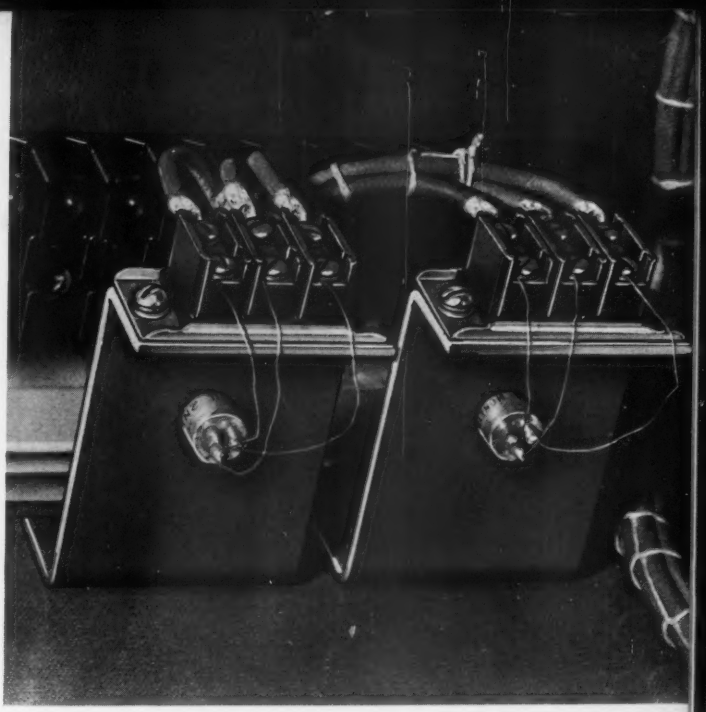
Figure 2 is a simplified schematic diagram of a typical voltage regulator. The voltage-sensing element, a conventional nonlinear bridge, measures part of the rectifier output voltage. The bridge balances at only one particular value of the input voltage. Any deviation of this voltage causes an output from the bridge which is amplified by a two-stage transistor amplifier and acts through the rectifier grid control to make the required correction. The rectifier output voltage is thus returned to the regulated

value. Adjustment of this regulated value is accomplished by varying the voltage-dropping resistance in series with the bridge. In this case, the nonlinear resistance of the bridge is made up of a group of ordinary incandescent lamps operated at greatly reduced voltage to insure long life. If parallel rectifier operation with existing dc generators is desired, an adjustable droop in the voltage output characteristic may be provided, as shown, by inserting an adjustable signal at the amplifier input proportional to the rectifier load current. After the installation has been completed, the rectifier can be made to share load with the existing machines simply by adjusting a small rheostat, until the rectifier characteristic matches that of the machines.

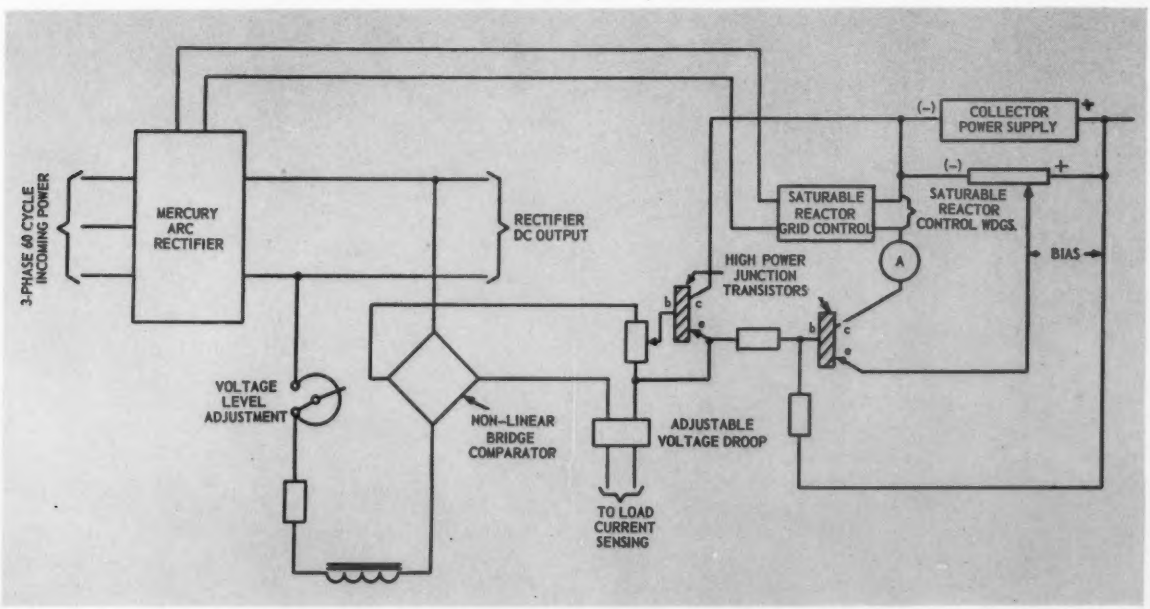
The output stage transistor is used to control the current in the control windings of saturable reactors in the grid phase-shift circuit of the rectifier. The power requirement of the saturable reactor control is well below the transistor maximum dissipation rating of 10 watts. In addition, a generous heat sink is provided in the form of a large ⅛-inch thick copper plate mounting which is so placed as to allow unrestricted ventilation. Figure 3 shows the transistors mounted on the copper plates. This ultraconservative application is expected to result in extremely long life of the transistors.

Ambient temperature rise was found to increase the emitter leakage current to a point that reduced the range of control undesirably. This effect was completely eliminated by using a small part of the collector supply voltage as a negative bias on the base of the output stage, as shown in Figure 2.

A number of rectifiers using this type of regulator have now been in service with excellent results for lengths of time from a few weeks to approximately a year. No trouble has been experienced. The transistor regulator has been adopted as standard for some sizes of mercury-arc rectifiers, and the application of transistors to other higher power control circuits is being contemplated. The accuracy obtained on present designs is approximately plus or minus ¼ to ½ percent. Greater accuracy can be easily achieved by adding an additional stage of amplification. However, realization of greater accuracy would be limited chiefly by difficulties in stabilizing the system.



HEAT SINK provides mounting for the transistor and its terminals and carries off heat generated in the transistor. **(FIGURE 3)**

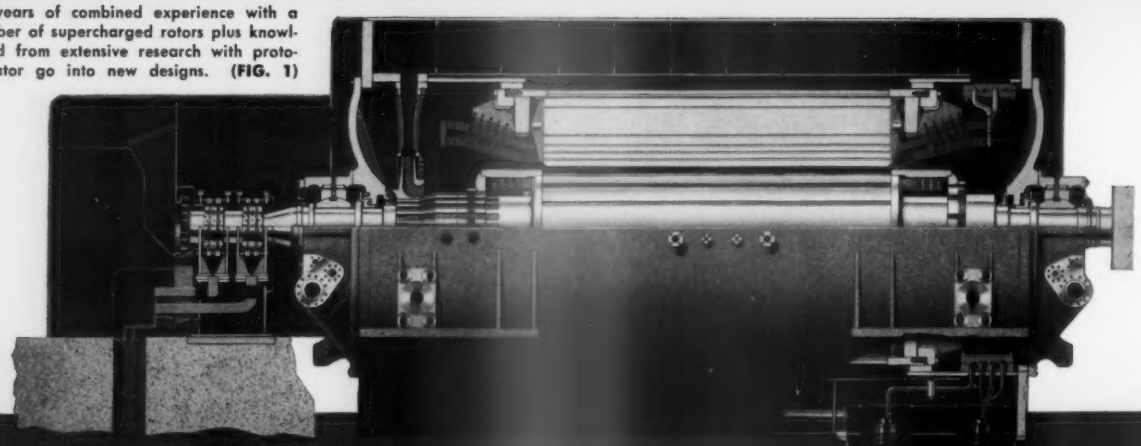


TWO SMALL P-N-P TRANSISTORS amplify deviations in the rectifier output and provide a strong signal to the saturable reactors in the grid phase-shift circuit. An adjustable droop is provided for parallel rectifier operation. **(FIGURE 2)**

COPPER PLANTS are working day and night to fill electrical industry needs. Slake lime from this 7.5-ft diameter by 180-ft long brick-lined rotary kiln is used to balance the flotation agent for processing copper ore. Despite its weight and massiveness, the kiln is rotated at 1.5 rpm with only a 40-hp four-speed cage motor. Limestone enters the kiln at the feed end (left) and is transformed in a period of two hours at 2300 F into slake lime which is discharged at the far end.

Allis-Chalmers Staff Photo by Clarence Hansen

OVER 23 years of combined experience with a sizable number of supercharged rotors plus knowledge gained from extensive research with prototype generator go into new designs. **(FIG. 1)**



Design Features of Today's...

LARGE TURBINE GENERATORS

by **L. T. ROSENBERG**
Chief Generator Design Engineer
Steam Turbine Department
Allis-Chalmers Mfg. Co.

Advances in turbine generator designs not thought possible just a few years ago are being built into today's units.

TURBINE GENERATOR DESIGN PROGRESS within the past six years has moved forward at an unprecedented rate. The successful completion of the first 70-mva generator with supercharged rotor[1, 2] in 1951 marked the beginning of a new era in capabilities. It was predicted a year later[3] that all large 3600-rpm turbine generators would ultimately be of this type. That forecast, already true for two-pole machines, now promises to become true for large four-pole units as well.

At 3600 rpm, generators ranging from 70 mva at ½ psig hydrogen inside the housing up to 147 mva at 30 psig are now available with supercharged rotors, while units of larger capacity are completely supercharged. At 1800 rpm, conventional cooling is likewise giving way to conductor cooling in ratings exceeding 147 mva at 30 psig.

Stator designs include new cooling

The general arrangement of a fully supercharged generator is shown in Figure 1. Perhaps the most striking departure from earlier two-pole machines is the heavily ribbed double shell rigid outer frame structure. The flexible member for the core mounting consists of a third cylindrical shell supported at the ends by two shorter cylinders overhung from the end plates. The object of this design is to provide the strength and rigidity of the four-pole 1800-rpm yokes, while isolating from the outer frame the 120-cycle elliptical core deformation of large two-pole machines.

The grain-oriented silicon steel stator laminations are stacked on nonmagnetic dovetail bars and accurately aligned with the aid of cylindrical stacking guides. The clamping pressure on the finished core is transmitted through individually adjustable nonmagnetic fingers with two prongs bearing against each tooth. The force is applied at only one point, located at the center of the area of each finger to insure uniform pressure from heel to toe. Ventilation is supplied to the fingers at the discharge end by means of cool hydrogen fed from behind the core through radial ducts extending down to the finger tips.

New core cooling introduced

The core itself is cooled by axial ducts formed by punching holes in the laminations. This feature possesses a number of important advantages over earlier cooling methods involving radial flow of gas through ducts formed by I-beam spacers which comprised nearly 20 percent of the active core length. Since the copper heat is not drawn out through the major insulation walls, it is not necessary to cool the teeth as far below the copper temperature as with the conventional stator designs. The holes punched in the teeth do not exceed 5 percent of the tooth volume, leaving at least 15 percent more tooth iron for useful flux. The volume of the core region behind the slots consumed by axial ventilating holes is approximately 2 percent, leaving at least 18 percent more core iron. Although replacement of duct space with high grade, grain-oriented silicon steel laminations adds to the weight and cost of manufacture, the user benefits because it also reduces the volume of gas required to fill the generator. Moreover, elimination of the I-beam spacers avoids the inherent losses in these I-beams. These losses are appreciable at the high flux densities of modern machines.

Another important advantage of the axial cooling method stems from the fact that each lamination is in contact with the cool hydrogen. Heat flows along the steel punchings rather than from lamination to lamination through many successive layers of varnish as with radial flow ducts. Thermal conductivity is thirty-two times better

with the new method. As a result, internal core temperatures are low despite wide duct spacing.

Other gains made

By keeping the core cooling gas to a minimum, more of the blower output is reserved for the windings. At the same time, differential thermal expansion between copper and iron is minimized because the iron can be kept hotter than the copper up to an appreciable load and corresponding gas pressure, with little or no difference in expansion. Moreover, with axial cooling the core temperature variation from one end of the machine to the other will better match the variation in the copper temperatures, thus alleviating relative movement within the slot length.

Core tightness is provided by two nonmagnetic steel spring disc pressure plates having a substantial deflection when the core is fully compressed. The deflection of these giant Belleville washers can be calibrated at initial assembly so that the exact core pressure may be determined at any subsequent time.

Stator coils of large turbine generators are composed of many thin strands of Class B insulated copper employing the newly developed 540-degree transposition to eliminate both slot and end-induced eddy voltage problems.[5] In supercharged stators, nonmagnetic steel cooling tubes of high electrical resistivity are embedded in the coils to provide a path for the gas in close proximity to the copper strands. The tubes are insulated with a thin layer of silicone rubber that conforms to the contour of the strands, filling the voids and insuring good heat transfer.

The compact design of large turbine generators and their ever-increasing current ratings have made it desirable to shield the solid frame structure from the stray fields in the coil end region. Figure 1 shows a series of flux shields of grain-oriented laminated steel, mounted behind the stator coil ends. The complete rings formed by these flux shields also serve to reinforce the stator coil support assembly.

Rotor manufacturing techniques improved

The rotors of large turbine generators are forged in one piece from ingots of nickel-moly-vanadium steel. In four-pole generators requiring the largest forgings, mechanical stresses can be held low enough to permit somewhat higher ductility than in the smaller diameter 3600-rpm rotors.

Metallurgical advances have been paralleled in recent years by improved inspection techniques. Rotors undergo four successive ultrasonic tests, periscope inspection, microstructure examination, magnetic particle tests, and sulphur print examination, in addition to the usual physical tests and chemical analyses. Test bars are also removed for magnetic permeability studies. Figure 2 shows three typical rotors.

The rotor coils are cooled through longitudinal ducts formed by milling a concave bevel along the edges of the silver bearing hard-drawn strip copper turns. This design affords ample surface contact area, a duct configuration having a low friction loss, and ease of entry and discharge of the cooling gas. The windings are held in place by high strength nonmagnetic steel wedges ground to a precision fit into the milled wedge notches along the rotor teeth.

The coil ends are securely blocked, as shown in Figure 3, and enclosed with nonmagnetic steel retaining rings shrunk over the generously proportioned shoulders at both ends of the rotor body. The leads are carried to the collector rings through radial studs that are mechanically supported with insulated steel collars threaded into the rotor forging. Heavy semi-circular bus bars, completely assembled and insulated as a unit prior to installation, conduct the current to shorter studs located between the collector rings.

Present-day compact designs not only save power plant space, but also greatly alleviate thermal and mechanical problems. Many new design features have been introduced to meet the more exacting requirements of dependability associated with ever-increasing capabilities.

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3. "Temperature and Load Limitations in Large Turbine-Driven AC Generators," L. T. Rosenberg. Presented before Southeastern Electric Exchange, Atlanta, Georgia, August 25, 1952.
4. "Test Report on a Fully Supercharged Generator," S. Beckwith, B. M. Koetting, L. T. Rosenberg, and G. W. Staats. AIEE Publication, *Power Apparatus and Systems,* April 1955.
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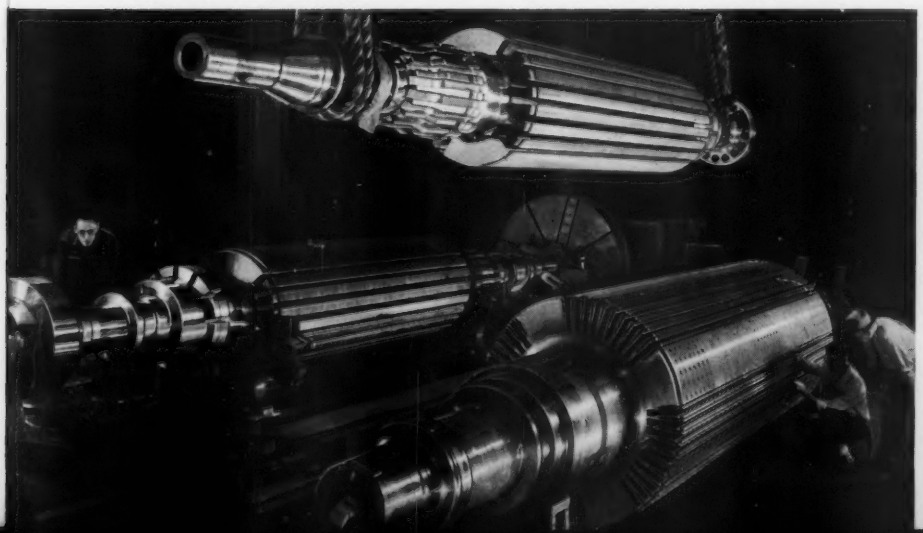
OVER 500 mva is represented by three rotors. Rotors in foreground will go into first 300-mw turbine generator. Two-pole machines will have supercharged hydrogen-cooled rotors and stators. **(FIG. 2)**



SECURELY BLOCKED, coil ends will be held in place by nonmagnetic retaining rings. Rotor shown is for a 75,000-kw, 13.8-kv, 3600-rpm turbine generator and will have supercharged cooling. **(FIGURE 3)**

Distribution System Studies

FOR INDUSTRIAL PLANTS

PLANT distribution systems vary widely in complexity. Yet, continuity of service is important in all systems.

by D. DALASTA
and
FRANK NOLAN
Switchgear Dept.
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Your plant distribution system can become dangerously inadequate overnight. Advanced warning can be gained by selective systems studies.

THE APPLICATION OF INDIVIDUAL COMPONENTS of distribution systems is reasonably well standardized. Items such as transformers, circuit breakers, and motors have standards publications prepared by NEMA, AIEE and ASA, covering rating, application, and testing of these devices. However, their coordinated use on a complete industrial system creates problems outside the scope of these publications. Since no two plants are alike, each distribution system has its own problems which must be studied in light of conditions peculiar to that installation. These distribution problems are:

1. Short-circuit conditions, including interrupting and momentary requirements of circuit breakers as well as relay coordination.

2. Load flow problems, such as line loading, voltage conditions, and reactive power distribution.

3. Stability considerations involving generators, synchronous and induction machines, and utility tie circuits.

4. Motor starting and other load swings affecting lighting, contactor drop-out, power rectifier operation, and plant motor torques.

5. Choice of the best system grounding practice for each installation.

6. System design covering modernization and expansion programs.

Methods of attack vary

Some system problems can be readily solved. For example, the short-circuit and momentary currents at any point in a radial system can be easily calculated. In Figure 1, a radial system is shown with the necessary circuit data for approximating the required interruption rating of the circuit breakers. With the exception of some reactance values which must be obtained from the manufacturer's design or test sheets, all of the necessary data can be obtained from equipment nameplates.

Figure 2 shows the mva contributions of each of the sources. These are tabulated with other circuit data in Table I. For example, the generator contributes 93.8 mva to a bus fault. The total mva for a bus fault equals the sum of the contributions of all sources, and this total is 450.5 mva. This value, when corrected by the appropriate multiplying factor, is used in choosing the proper circuit breaker. For a 5-cycle air magnetic breaker a 1.1 multiplier is used, and a 500-mva breaker would be adequate for fault interrupting duty. Other factors such as con-

tinuous and short-time current ratings must be considered in this selection. Note that the induction motor contribution was ignored in determining the interrupting ratings. The contribution must, however, be included in the momentary calculations.

Plant distribution systems vary markedly in degree of complexity. Today's engineer has a choice of several methods of analysis:

1. Arithmetical calculations.
2. Dc network analyzer.
3. Ac network analyzer.
4. Digital computers with or without ac network analyzer.

Arithmetical

The example illustrated by Figures 1 and 2 demonstrates the arithmetical method.[1] On a more complex system it becomes obvious that, although possible, a solution by slide rule methods is tedious and time consuming. In the past years the large utilities employed a battery of specialists wielding slide rules to obtain the information needed to properly apply circuit breakers, relays and other circuit components.

When properly applied to the study of distribution systems, a network analyzer eliminates many hundreds of hours of slide rule work.

Dc network analyzers

Today, there are many dc boards[2] throughout the country. They have a number of variable resistances which can be used to represent circuit reactances. In three-phase short-circuit studies the results obtainable on the dc boards are satisfactory. Furthermore, they are useful in network simplification and other studies, are simple to use, and answers can be quickly obtained. Dc analyzers cannot be used for studies in which the angle between voltage and current is significant. Thus load studies covering (a) voltage conditions, (b) var-flow, (c) transformer taps, (d) generator loading, and (e) tie line loading are generally outside of the scope of the dc analyzer. In addition, stability studies cannot be made on dc boards.

Ac network analyzers

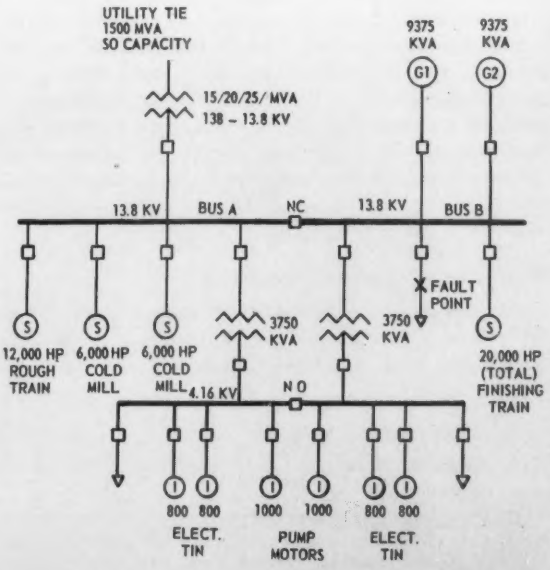
Because of their adaptability to complex problems, ac analyzers have been accepted as the main tool for system analysis. There are less than 50 ac network analyzers available in the Western World, and because of the limited demand for them, only a few companies have engaged in their manufacture. The first board was made in 1929, and since then no more than a few have been installed each year. A typical modern ac network analyzer is shown in Figure 3.

In preparing a system for representation on an analyzer, attention must be given to fitting the actual circuit characteristics to the ranges available on the board. Doing this requires a knowledge of both the system to be studied and the limitations and possibilities inherent in the equipment. The plant engineer, except in isolated instances, cannot be expected to be a specialist on the network analyzer. Skilled operators are available at these installations to assign the circuits, operate the instrument desk and give other valuable assistance. In preparation for the study, the engineer must compile the system data required for the studies. Studies may involve rotating machine loads, ratings, and impedances; transformer ratings, taps, and impedances; reactor ratings and impedances; line and load characteristics; circuit breaker ratings and speeds;

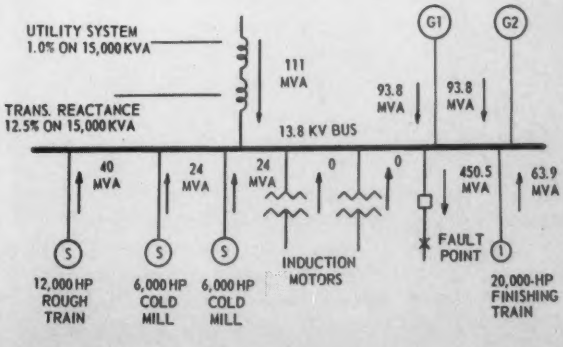
TABLE I

Source	Kva	Hp	X"d	X'd	Mva Contrib.
Gen. No. 1	9375	—	10%	—	93.8
Gen. No. 2	9375	—	10%	—	93.8
Utility	—	—	—	—	111.0
Roughing	—	12,000	—	24%	40.0
Cold No. 1	—	6,000	—	20%	24.0
Cold No. 2	—	6,000	—	20%	24.0
Finishing	—	20,000	—	25%	63.9
Induction	—	—	—	—	—
		Total Symmetrical Mva			450.5

Tabulation of ratings, reactances, and short-circuit contributions of the various components of the system in Fig. 1.



COMPLETE data are needed when checking the interrupting rating of circuit breakers. Radial system shown has necessary data. **(FIG. 1)**



MVA SHORT-CIRCUIT CONTRIBUTIONS that system components are capable of making are shown on a simplified system diagram. **(FIG. 2)**

NETWORK CALCULATORS are used in planning and analyzing power systems. Through their use small-scale system analogues are set up, reproducing the electrical characteristics of system generators, transformers, transmission lines, and loads both existing or proposed. Studies are made under normal and abnormal operating conditions. Results reveal adequacy of system components.

and relay characteristics. The necessary data are tabulated and converted to a common base so that the proper values can be set in the network analyzer. The operator connects the individual analyzer components into a network similar to the system single-line diagram provided by the plant engineer. The reading and recording of data then begin. Usually a reproducible copy of the single line is used to record the data for each system condition.

These analyzers include reactors, resistances, capacitances, autotransformers, mutual transformers, as well as generator units. These components can be combined to represent rotating machines, lines and cables, transformers, and loads. The latest boards are designed so that one can set the percent impedances and percent susceptances directly on the calibrated dials, since base impedance and ohms impedance are the same. The operator is able to read volts, amperes, watts, vars, phase angle and vector components at any point on the system by means of a pushbutton circuit selector arrangement at the operator's desk. Circuit identification lights at the recording desk eliminate possibilities of errors in recording data.

Short-circuit studies most critical

Proper short-circuit protection is perhaps the most critical of the plant electrical engineer's problems. The penalties for negligence in this respect are expensive. They include:

1. Physical danger to personnel.
2. Extended damage to equipment.
3. Prolonged unplanned shutdowns.

Short circuits of 500,000 to 1,000,000 kva and more are available on some 2400 to 13,800-volt plant busses. Faults of such magnitudes may exceed the interrupting ratings of all standard protective devices. When a fault occurs, the circuit breaker or other protective device must be able to interrupt the available current. Undersizing cannot be tolerated. A circuit breaker properly rated yesterday is not necessarily adequate for today's service. System changes nearly always add to the system fault capacities. Added generation, heavier tie lines, larger supply transformers, and greater motor feedback are all factors increasing the fault duty required of the protective circuit breakers. Dc or ac network analyzers allow a convenient means of obtaining fault duties at all system busses for any number of system conditions. If a plant generator is due for overhaul, it may mean closing tie circuits to supply all busses adequately. If a normally energized supply cable fails, perhaps a bus-tie breaker must be closed to carry the load. Where in the electrical system can a new process line be most economically located? These are typical of the conditions for which data can be recorded during a board study and later thoroughly analyzed.

Proper circuit breaker ratings derived

Only three-phase short-circuit studies are necessary in most industrial plants. These faults give the largest current magnitudes, since grounding impedances practically always limit the line-to-ground fault currents to lesser values. Two values of fault current must be calculated for plant systems 2.4 kv and above:

1. The rms symmetrical value of the fault current flowing at the instant that the circuit breaker contacts part. This value is equal to the circuit breaker interrupting current for an 8-cycle breaker. Standard multiplying factors are used for the interrupting currents for faster breakers and take into account generator decrement and fault current dc offset.

2. The rms asymmetrical value of the fault current at one-half cycle after the fault occurs. This is termed the momentary current and is the value which determines for all equipment the mechanical stresses resulting from the high fault currents. The symmetrical value at one-half cycle after fault is first calculated. Then a multiplying factor, usually 1.6, is applied to obtain the asymmetrical value. This momentary value is also important when considering the circuit breaker operating mechanism requirements for closing against a faulted circuit.

Since the ability of rotating machines to produce fault current diminishes with passage of time after initiation of a fault, different values of reactances are used for the two calculations listed above. Due to the speed of modern breakers, the subtransient reactances for synchronous generators are used in both cases. Present standardized methods for simplified calculation of fault currents have been adopted by AIEE[3] and ASA[4]. The recommended machine design reactances and multiplying factors which should be used are included. Revised methods are being seriously considered by AIEE[5].

Short-circuit currents reduced

During an analyzer short-circuit study it is convenient to try various schemes to reduce fault currents as the study progresses. Some of the possibilities are:

1. Splitting busses and loads.
2. Opening tie circuits.
3. Addition of current-limiting reactors in tie, generator, or feeder circuits.
4. Utilizing duplex-type reactors.

5. Tying system busses together at a higher voltage (usually utility supply voltage) through transformers.

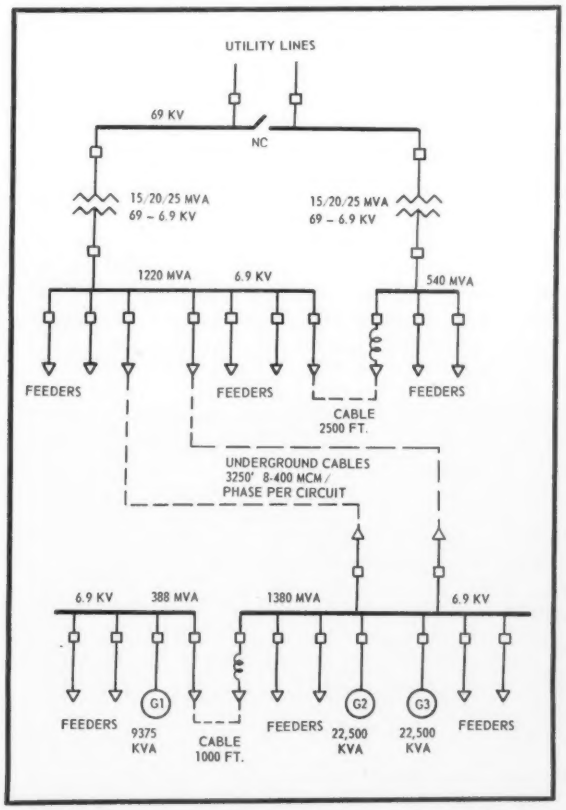
6. Rewinding old generators or adding new machines at higher voltages.

The primary intent in the application of fault-reducing measures should be to keep fault currents down to a reasonable value and within the ratings of standard breakers. To try to match the system to the limited interrupting capabilities of old breakers can be a serious mistake, since the resulting system may not be stiff enough to maintain suitable voltage levels, especially during motor starting and other disturbances.

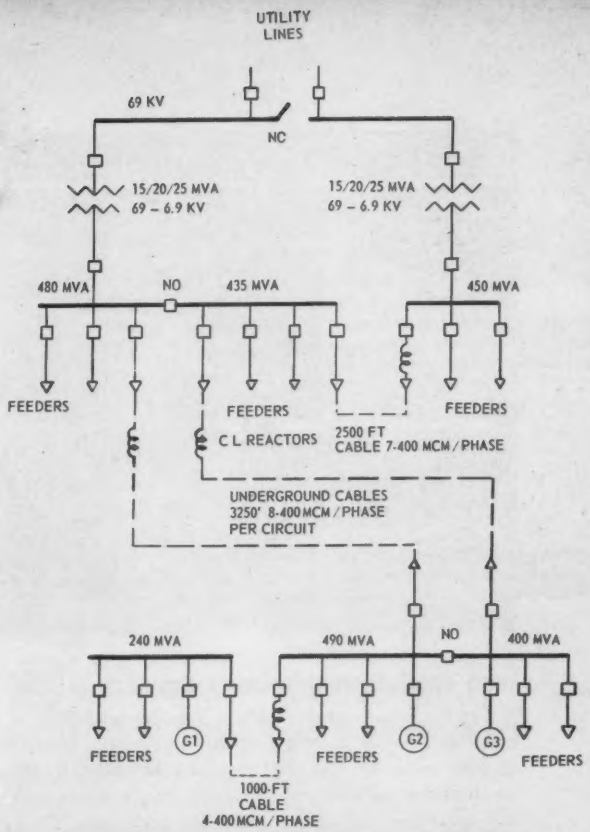
Short-circuit study illustrated

An example of the results of a typical short-circuit analysis is illustrated in Figures *4a* and *4b*. Figure *4a* shows fault capacities of more than 1200 mva present on both main 6.9-kv busses. The maximum interrupting capacities of the feeder circuit breakers when new were 500 mva. These breakers would certainly fail in attempting to interrupt this fault. Physical danger, equipment damage and extended outages would almost certainly result.

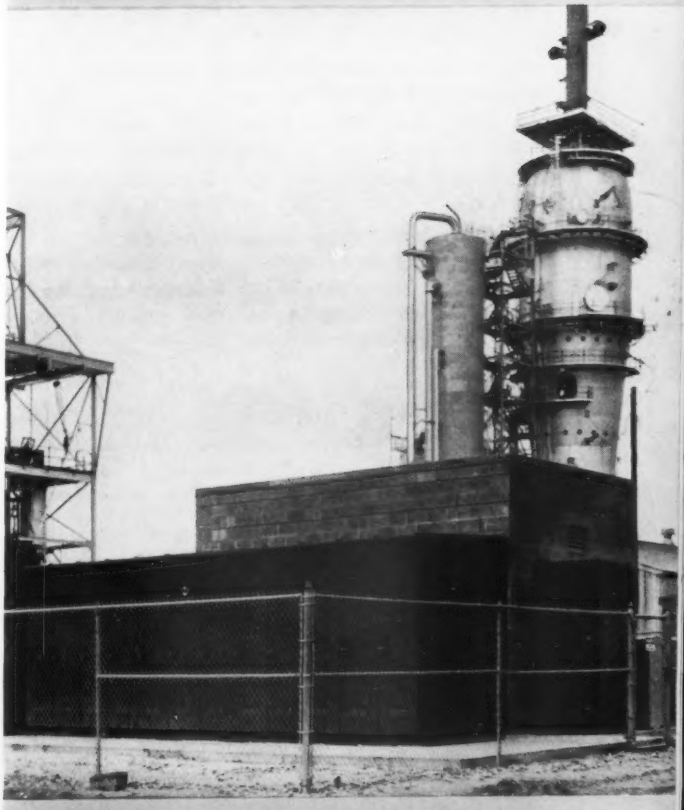
Figure *4b* shows the results of a short-circuit study to alleviate this condition. The addition of two current-limiting reactors plus sectionalizing two busses attained the desired result. Fault capacities were reduced to less than 500 mva.



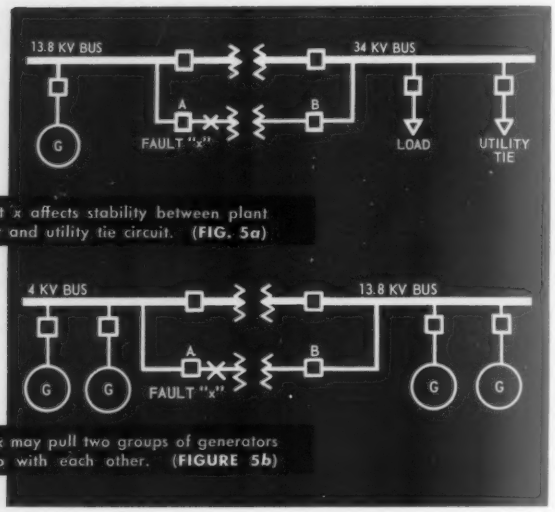
SYSTEM IN DANGER of serious trouble is revealed by study which showed circuit breakers could not interrupt possible fault. **(FIG. 4a)**



BUS SECTIONALIZING and current-limiting reactors added to circuit of Figure 4a reduce fault mva values. **(FIGURE 4b)**

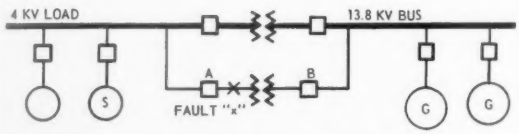


TYPICAL SUBSTATION, rated 3000 kva, 34,400-2400 volts, is choice for southwestern oil refinery distribution system.

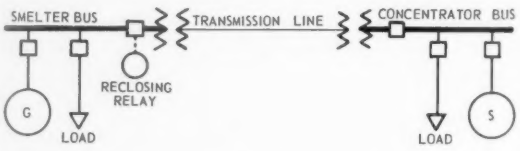


FAULT at x affects stability between plant generator and utility tie circuit. **(FIG. 5a)**

FAULT at x may pull two groups of generators out of step with each other. **(FIGURE 5b)**



FAULT at x may cause synchronous motors to pull out of synchronism, resulting in a shutdown. **(FIGURE 5c)**



FAULT on the transmission line between ends of the system might cause the synchronous motor to pull out of step. **(FIG. 5d)**

Load studies provide many answers

Utility load studies represent the greatest work load of the usual ac network analyzer. In large industrial plants such as steel mills load studies can also be quite important. Load studies provide data covering bus voltages and mw and mvar flow for various operating conditions. Thus they can be useful for those plants where the following types of problems are present:

1. Low or high voltages at various busses.
2. Problems involving ratings and range of taps on transformers.
3. Critical loading on lines, cables, transformers, generators, and other equipment.
4. Size and location of power-factor correction equipment.
5. System changes which affect any of the above considerations.

Smaller plants having radial systems can usually be analyzed without the use of the ac network analyzer. Plant load studies with or without the ac network analyzer can provide benefits through improved voltages, better power factor and reduced power costs.

One characteristic of industrial systems as compared to utility systems is that for any voltage level there is generally low reactance between busses. This low reactance results in a minimum of voltage problems. Between voltage levels, the reactance of step-down transformers is sizable. However, if the load power factor is high, the voltage drop across the transformer is small, since the voltage is merely shifted in phase angle but not changed much in magnitude. Long overhead and cable circuits can add appreciable impedance, especially if they are a mile or so in length. A well-designed plant distribution system avoids transferring large blocks of power long distances except at the higher voltages—thus minimizing this voltage drop problem.

Stability studies are becoming important

In most industrial installations, system stability problems have been given limited study. The term "stability" is used here to describe the degree of irregularity in power supply to plant load occasioned by a disturbance such as a fault. One simple example is a fault at point *x* in Figure 5*a* which is cleared by transformer differential relays tripping circuit breakers *A* and *B*. During the period when the

TABLE II

System Condition	Circuit A B C D	Minimum Voltages at Bus	Minimum Voltages at Motor	Accelerating Volt. at Bus	Accelerating Volt. at Motor	Starting Torque at Motor
I	x — — —	68	63.5	88	82.5	67.5
II	x — — x	70	64.5	75	69.5	48.0
III	x x — —	81.5	75.5	100	93	86.5
IV	x x — x	83	77	100	93	86.5
V	x — x x	92	86	98	92	84.5
VI	— — x x	89	83	89	83	69.0

NOTE: All values are in % of normal values. x — — — Denotes breaker in closed position. A, B, C, D Refer to specific breakers in Fig. 6.

Estimated values of minimum and accelerating voltages and motor starting torques for circuit conditions specified in Fig. 6 when starting 2000-hp synchronous motor.

fault is on, the plant generators will speed up and tend to swing ahead of the utility system. If the fault persists long enough, the two sources will swing apart, causing a partial or complete shutdown. Figure 5*b* illustrates a condition in which two groups of plant generators may lose synchronism with each other. In this case a fault at *x* will tend to pull the two generating groups apart, especially if the fault is cleared slowly and if most of the plant load is located at one or the other bus. Large synchronous motors can take the place of one of the sources. Figure 5*c* illustrates this possibility. Here again a fault at point *x* will tend to pull the synchronous motors out of step. The relaying and circuit breaker speeds are decisive. Generally, when a synchronous motor falls out of step, its protective equipment removes it from the line. Thus the major consequence is usually loss of the synchronous motor itself, as the remainder of the system will probably ride through the disturbance.

In all of the above examples the system voltage profile in the face of a bus short circuit is important. Some plants lose the entire load upon the occurrence of a bus fault. The reasons for this are twofold:

1. All busses are operated with tie circuits always closed. With concentrated heavy loads these tie circuits have little impedance, and consequently a fault on one bus practically amounts to a fault on all busses.

2. Old slow-speed oil breakers with slow relay settings do not clear the faults fast enough.

As a consequence of these conditions, the bus voltage drops, motors all decelerate, and the supply sources are not able to pull the entire load back up to normal when the fault is finally cleared. Induction motors as well as synchronous motors are adversely affected in this manner, and thorough stability studies[6] are recommended for critical processes. For the condition of prolonged low voltages at distribution busses motor stability can be improved by installing motors with higher torque characteristics, and contactor drop-out can be minimized by introduction of time delay in the drop-out time, or installing contactors with low drop-out voltages.

A common stability problem found in utility systems, but not generally present in most plants, occurs where overhead lines tie various machines together and reclosing relays are used to restore the circuits after temporary faults.

Some mining installations with the smelter remotely located from the concentrator require transmission lines through mountainous areas. Reclosing relays are used to prevent prolonged shutdowns resulting from temporary faults on the power line. A question that should be checked is whether the synchronous motors driving the mills will stay in synchronism through a transient disturbance resulting from a fault on the lines. This condition is illustrated in Figure 5*d*.

Whenever important stability problems similar to those described are recognized, they can be solved on the ac network analyzer. Several runs with varying system conditions and clearing speeds are necessary if unstable conditions are approached. Typical solutions to system stability problems may be:

1. Adding a tie circuit.
2. Using faster relay settings.
3. Installing modern 3- and 5-cycle breakers.
4. Reconnection of feeder circuits to different busses.

Motor starting problems solved

In those plants not having arc furnaces, full-voltage starting of large synchronous or squirrel-cage induction motors usually creates the greatest normal operating voltage disturbance. While practically all newer motors are designed so that they can successfully withstand full-voltage starting, the adverse effects on the power distribution system must be recognized. The most important considerations are:

1. Initial minimum voltage droop resulting within the first several cycles after energization. This minimum voltage determines whether other contactors supplied from same bus or nearby points will drop out. Light flicker, synchronous motors pulling out of step and induction motors stalling are common results of excessive voltage dip.

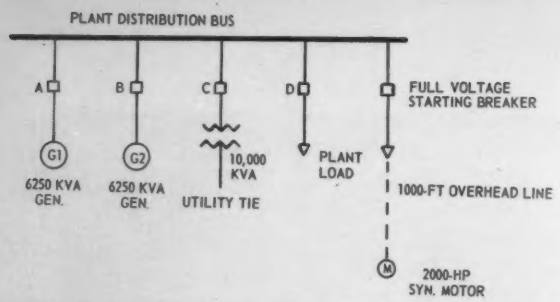
2. Restored voltage, or that voltage existing after automatic regulating devices have acted. For cases where mill generators are equipped with modern regulators the voltage will recover quickly due to the immediate increase of generator field excitation. The magnitude of the restored

TABLE III

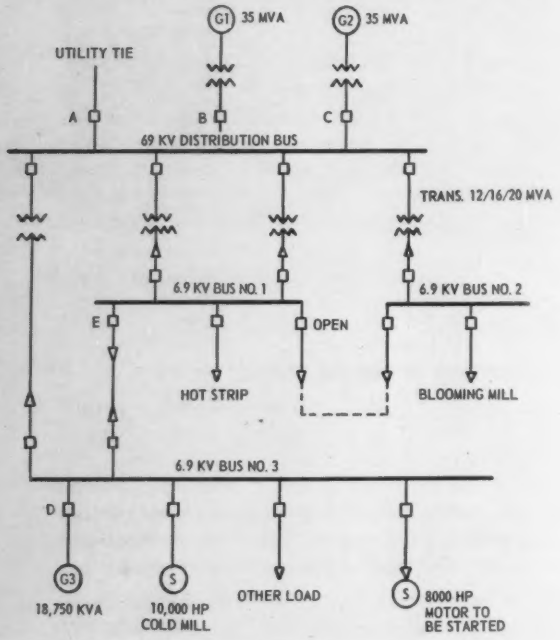
System Condition	Circuit	6.9-kv Bus No. 1		6.9-kv Bus No. 2		6.9-kv Bus No. 3		69-kv Bus	
	A B C D E	R	D	R	D	R	D	R	D
1	x x — x —	98.8	98.8	98.0	98.0	89.0	87.0	98.7	99.0
2	— x — x —	94.0	93.0	93.6	92.5	87.0	84.2	94.1	93.0
3	— x x — —	93.3	91.5	93.0	91.0	78.5	72.0	93.4	91.5
4	— x x — x	87.6	85.0	91.5	89.9	86.5	83.6	92.0	90.1
5	— x — — x	84.4	80.7	87.8	85.0	83.2	79.1	88.4	85.5
6	x x — — x	92.9	91.6	97.2	96.8	91.6	90.0	98.0	97.4
7	x — — x x	94.0	93.2	97.0	97.0	93.2	93.2	97.8	97.4
8	x — — x —	98.7	98.4	98.2	98.0	89.2	87.1	99.0	98.7

x — — — — Denotes circuit breaker is in closed position. A, B, C, D, E Refer to "Running" or "Down" condition of 10,000-hp synchronous motor of 6.9-kv Bus No. 3.

Percent of normal bus voltages resulting from full-voltage starting of 8000-hp motor on typical system of Fig. 7.



SIMPLIFIED distribution system diagram will help the engineer determine the effects of full-voltage starting of a large synchronous motor. Results in this case were tabulated for six conditions. **(FIG. 6)**



STARTING an 8000-hp synchronous motor on the 6.9-kv bus can create a number of problems involving the distribution system. **(FIGURE 7)**

voltage at the motor will determine if the motor can develop enough starting torque for the application and continue to develop more torque than the load demands throughout the accelerating period. At the end of the accelerating period synchronous motors must have sufficient torque to pull into step. Low restored voltages at busses can damage local contactors by reducing contact pressure and in some cases also burn out operating coils.

For starting larger motors there is the alternative of accepting the increased costs of reduced-voltage starting equipment or tolerating the system disturbances. A survey must be made to determine which of the above hazards are likely to occur. Then a study of minimum and restored voltages must be made for the various conditions under which the motor will be started. This type of study can usually be limited to the portion of the distribution system supplying the motor to be started. This simplification allows one to estimate the resulting voltages to within a few percent. However, some systems are closely knit, and all busses are affected appreciably. If the equipment which is vulnerable to voltage droop is not adjacent to the motor being started, then the whole system may be involved and a network analyzer study necessary. More detailed system performance as well as alternate system operating conditions can then be investigated. Load considerations such as the beneficial effects of synchronous motors can also be included, since this work is not usually too involved. These motor-starting studies can conveniently be conducted during the final day of a system study.

Table II shows the resultant bus and motor voltages occurring when starting a 2000-hp motor for six different system conditions. A single-line diagram is shown in Figure 6. The voltages were estimated through the use of curves and slide rule calculations.

In the system of Figure 7 the effect of full-voltage starting of an 8000-hp synchronous motor on bus No. 3 is under consideration. The results of this motor-starting study are tabulated in Table III for eight different system conditions. The study included the beneficial effects of a 10,000-hp synchronous motor running unloaded on the same bus. Because of the tie circuits, this latter problem was better adapted to the network analyzer.

System grounding requirements checked

System grounding in distribution systems involves many considerations. Existing equipment, method of operation, nature of load, sources of power, availability of equipment neutrals, type of feeder lines, lengths of cables, presence of surge capacitors, and experience of operating and maintenance personnel all have a direct effect in the grounding picture. Yet the choice of an adequate, if not the best, grounding scheme for any particular installation is not complex. The reason for this is that, for practically all systems, each voltage level can be studied without regard to the other voltages within the plant. The only requirement is that there be at least one delta winding in the two-winding transformers between these voltages. Ground disturbances existing at one voltage cannot be transferred through the transformers to the other systems. In plants using radially fed transformers supplying loads through radial feeders, each transformer secondary system can be treated as a separate problem, even though several may be at the same voltage level. The nature of the load may indicate different schemes of grounding for system segments at the same voltage level. The ac network analyzer is not particularly useful in the consideration of grounding problems.

Many systems are operated successfully without intentional connection to ground. Past experience has shown that some of these systems have excessive insulation failures resulting from transient overvoltages. Low resistance grounding has usually been successful in alleviating these problems.

The details of the various grounding schemes commonly used in industrial plants are readily available.[7] At the high distribution voltages (usually 34.5, 69, and 138 kv), lightning arresters, transformer insulation, and utility relaying requirements are the predominant factors. Solidly grounded systems at these voltages are common.

Medium voltage grounding analyzed

In the medium distribution voltages, 2.4 to 13.8 kv, concern centers around obtaining enough current for ground relaying but not enough to cause expensive damage, such as burned iron laminations in motors or transformers. In resistance grounding the I^2R loss in the resistor is kept low enough to prevent damage to a plant generator when the sudden ground fault resistive load is applied. Probably most commonly used is a grounding resistor suitable for limiting the maximum line-to-ground fault current to a value between 1.0 to 1.5 times the rating of the current transformer in the largest feeder, but not less than 5 percent of the three-phase fault current. It is generally sufficient to use the following approximation:

$$R = \frac{V_{L\text{-}N}}{I_{L\text{-}G}}$$

where R is resistor ohms, $V_{L\text{-}N}$ is the line-to-neutral voltage, and $I_{L\text{-}G}$ is the maximum line-to-ground fault current arbitrarily selected in the manner stated above.

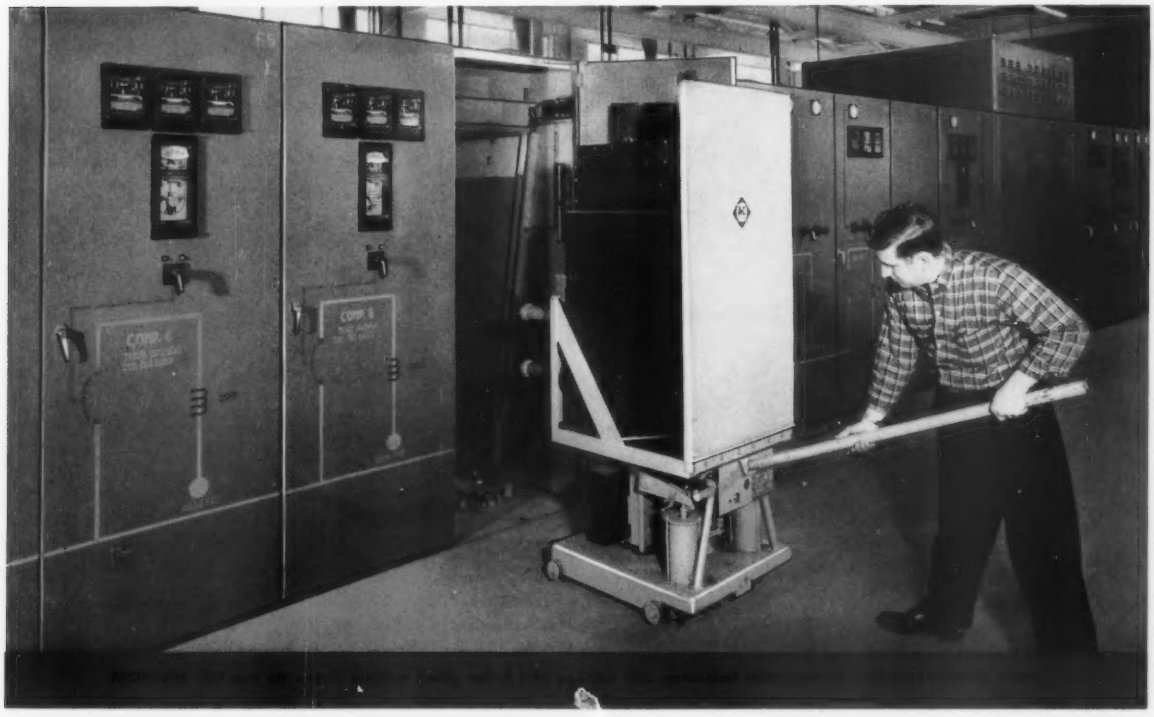
If a plant generator is used to carry base load, the resistor can generally be located in its neutral. If the supply transformer secondary is wye connected, that neutral point can be used. An alternate grounding point is desirable for those periods when the grounded generator or transformer is out of service. Two simultaneous grounding points to eliminate the necessity of switching grounding devices are used in some installations. Where the ground fault currents are limited as suggested in the preceding paragraph, there is not much danger from circulating currents through the grounding devices. Where no neutral point is available, it is common practice to install a zigzag grounding transformer and connect the resistor to its neutral.

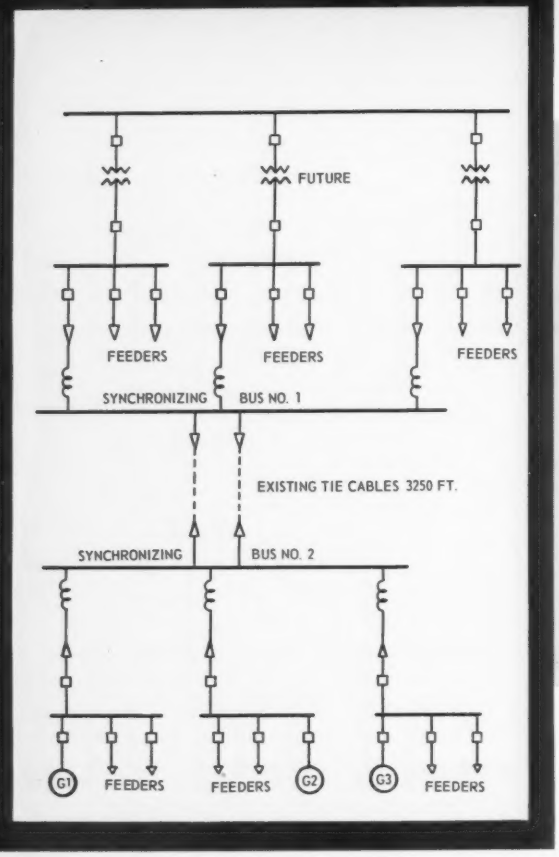
Reactance grounding is inferior to resistance grounding in most systems. Extremely low impedance grounding is avoided because of the high ground fault currents involved. Where plant generators are applied in generator-transformer unit connection, a standard single-phase distribution transformer with resistance loading is recommended.

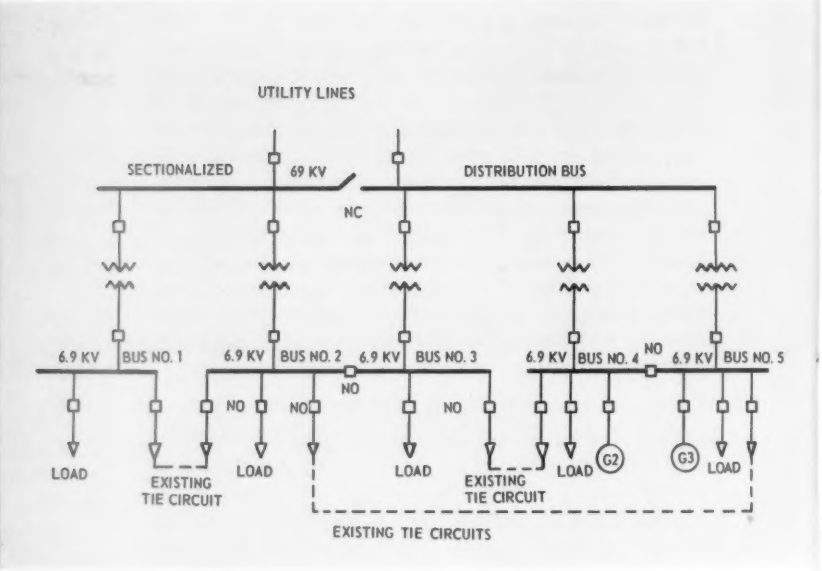
While every circuit outage is undesirable, some loads are extremely critical in this respect. High resistance grounding schemes have been applied successfully to eliminate a circuit breaker operation upon the occurrence of a ground fault. Such schemes merely sound an alarm or give some other indication that a ground fault is present. The trouble is then located and corrected when convenient. The principal advantage of high resistance grounding over an ungrounded system is that, when properly applied, the system is relatively free of transient overvoltages which plague certain ungrounded systems. It is believed that the success of high resistance grounding schemes in the face of line-to-ground faults is in a great measure dependent upon efficient methods of locating faults and prompt action in removing them.

Low voltage grounding problems studied

Low voltage (600 volts and below) grounding problems are similar to those of the medium voltage class. Usually no intentional grounding impedance is added. High resistance grounding is sometimes applied in the same manner and for the same reasons as described for medium voltage systems. Solidly grounded transformer secondaries are quite often used when the neutrals are available. Low







ANOTHER ALTERNATE SCHEME for the study of future expansion of the system shown in Figures 4*a* and 4*b* uses radial system fed from a 6.9-kv bus that can be sectionalized. **(FIGURE 9)**

←

ALTERNATE SCHEME for system study covering future expansion of system shown in Figures 4*a* and 4*b* uses a double synchronizing bus arrangement with current-limiting reactors. **(FIGURE 8)**

resistance grounding is not generally applied for these reasons:

1. Circuit, ground, and fault impedances in low voltage circuits are appreciable. Since low voltage switchgear does not usually include ground relays (only phase series trip devices), there may be a lack of sufficient ground fault current to trip.

2. There are few plant generators at these voltages. Solidly grounding of generator neutrals imposes the risk of machine winding damage on a single line-to-ground fault. These windings are braced for a maximum current of the three-phase fault value. Single line-to-ground fault currents are greater than three-phase fault currents for solidly grounded machines.

Modernization and expansion possibilities evaluated

Changing a distribution system is done to handle present power requirements better and to accommodate future needs more readily. These improvements are slanted toward one or more of the following:

1. Reduction in power costs by means of better power factor, better demand factor, improved metering arrangements, and smaller firm purchased power requirements.

2. More reliable power sources and continuity of supply to loads by improved equipment giving better performance and requiring less maintenance and fewer outages. Also more flexible system using alternate circuits, allowing isolation of defective equipment, and provision for future changes.

3. Safety to personnel and equipment through adequately rated electrical equipment, in good condition and arranged so that a simple, logical and direct scheme of operation insures promptness in action with a minimum of human error.

4. Less maintenance in both labor costs and repair parts. This allows power distribution engineers to concentrate their time on forthcoming distribution requirements without being burdened with excessive breakdowns or maintenance problems which should be a matter of routine.

All of the previously listed studies—stability, short circuit, load flow, motor starting, etc.—can be considered a part of any modernization and expansion type of study. Yet the first and major basic problem to be solved is one of primary circuitry. This practically always amounts to a higher in-plant primary distribution voltage which may be an increase from 480 volts to 4.16 kv for the smallest installations, to perhaps a change from 34 kv to 138 kv in the largest plants.

In planning a distribution voltage change it must be recognized that certain fixed characteristics exist in each plant. Thus an economic analysis will limit practical solutions to a maximum of two or three schemes. The network analyzer can be of valuable assistance in the final choice of the distribution system. Each distribution system under consideration is in turn applied to the network analyzer. A study of short-circuit kva available at the various system locations will often give sufficient information for comparative purposes. This will check existing circuit

breaker sizes, current-limiting reactor requirements, give an indication of possible problems in the starting of certain large motors, and can be of some assistance in estimating stability problems. Momentary as well as interrupting requirements can be checked. Various operating conditions with certain tie links open or closed or with new ties added are covered. Future loads as well as varying power supply conditions are included.

One distinct benefit resulting from an analyzer comparison of two possible distribution schemes is that it gives the engineer an intimate "feel" of his system. This is, of course, a basic strong point of an analogue-type device, and its effect of improving the engineer's understanding of his system can be immediately recognized.

One possible expansion scheme for the system of Figure 4*a* is that shown by Figure 8. This utilizes a synchronizing tie bus at each end of the plant, with existing cables connecting the two busses. Reactors are necessary in each of six circuits. One serious disadvantage of this scheme is that a fault in any of the tie cables could shut down most of the plant load.

The same system can be expanded to that shown by Figure 9. The existing tie cables can be kept open at one end, ready for use in emergencies. Yet, during normal operation, a tie cable fault merely affects the one bus from which it is kept energized. This essentially radial arrangement is adaptable to step-by-step expansion without increasing the fault interrupting requirements of the 6.9-kv breakers.

After the most promising schemes have been proved workable, economic studies[8] as well as equipment and installation cost tabulations are necessary to select the best scheme.

Some plant distribution system engineers are conducting periodic studies with the aid of network analyzers to check the effects of system changes.[9] Industrial power systems are continually expanding and processes and machines will demand more reliable and uniform flow of electric power. To provide this service more engineers are learning to recognize new problems as they arise and are using the latest methods and computing devices in their solution.

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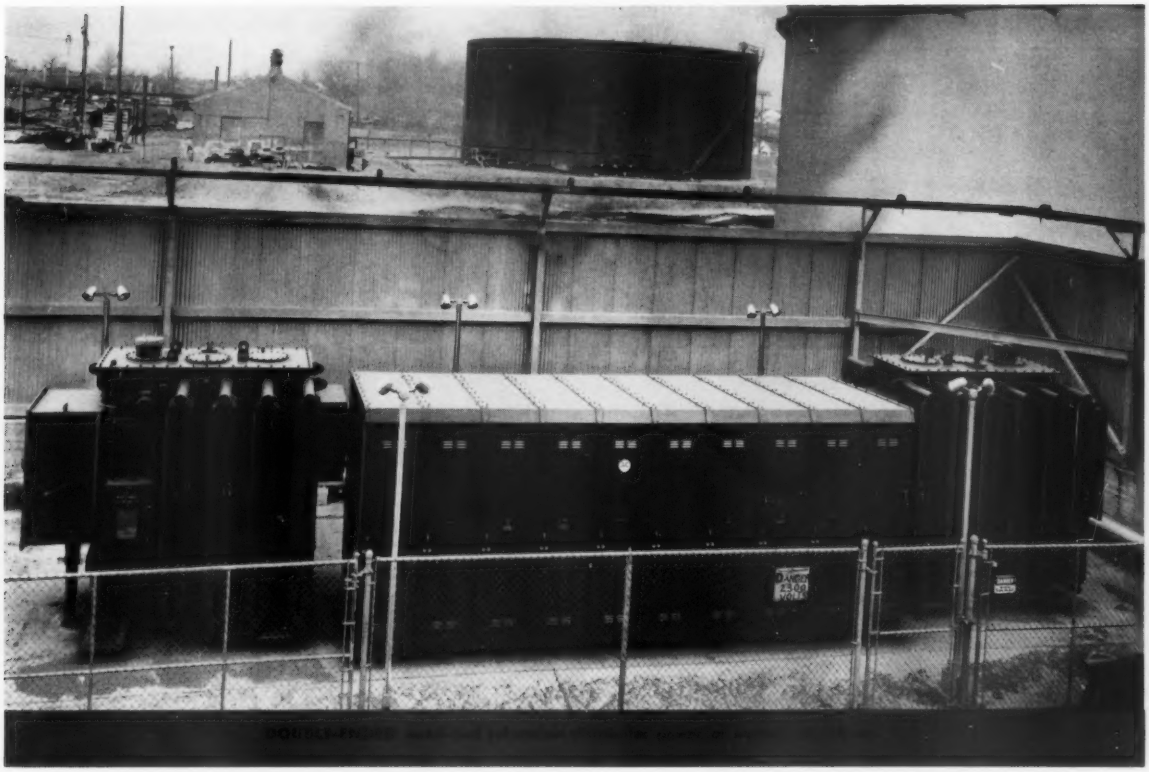
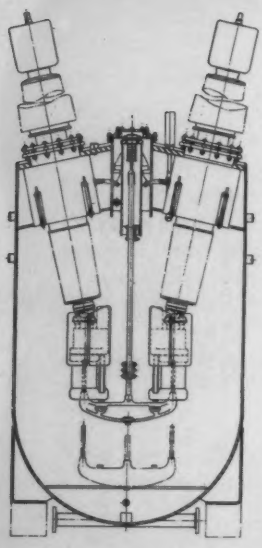
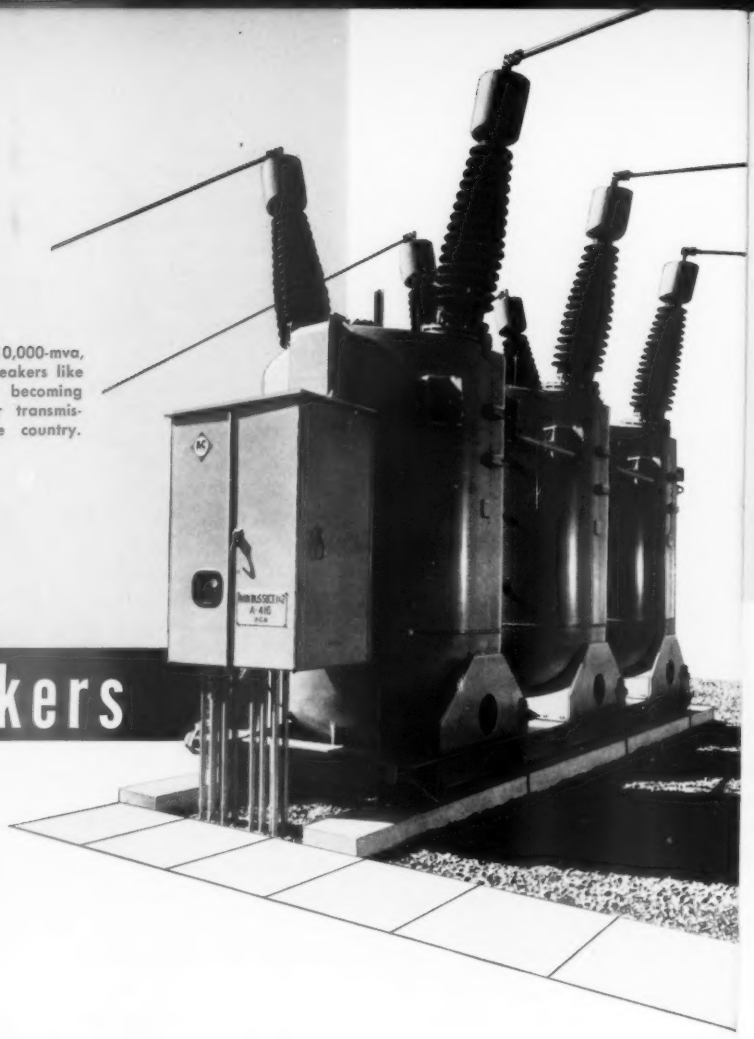




PNEU-DRAULIC OPERATED 10,000-mva, 1200-ampere, 230-kv circuit breakers like this three-cycle breaker are becoming more commonplace on power transmission systems over the entire country.



Transmission Breakers

PACE POWER GROWTH

by A. E. KILGOUR
Boston Works
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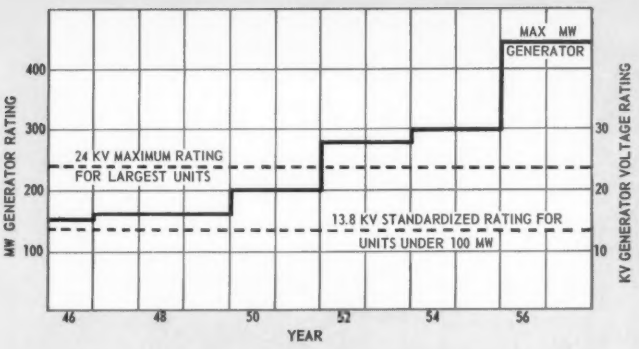
Circuit breaker engineers are meeting the challenge of growth in generator ratings and system complexity by keeping ahead of actual system needs.

CONTINUALLY INCREASING DEMANDS for more and more kilowatt-hours have resulted in more intricate system networks, greater concentration of power at each generating station and larger generator units. Figure 1 illustrates the trend toward larger generating units and shows the maximum sizes ordered in the past few years. Superimposed onto this growth curve is the range of generator design voltage, 13.8 kv to 24 kv, with 18,000 volts being the most common rating at present for larger units. Compared to the generator capacity growth, the voltage band has remained comparatively constant, and as a consequence the full-load current values have increased directly with the mva rating of the generators.

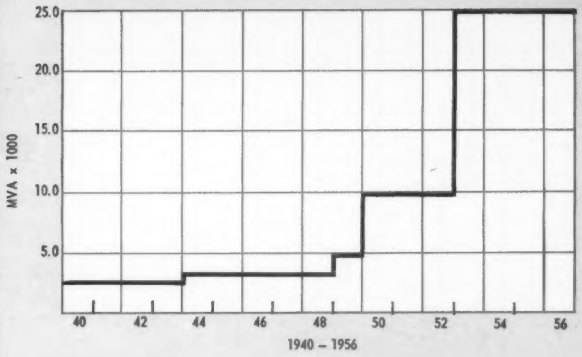
This growth of mva and full-load current has forced a significant change on the application of transmission and generator breakers. Where once a generator and generator breaker formed a unit, larger generator installations now include a combination of generator, generator transformer and generator breaker as a unit. This is an important change because it immediately elevates the breaker voltage to 69,000 volts or higher.

Breaker protects generator and transformer

Short-circuit protection for the transformer and generator against transmission system faults at these higher voltages is already available, since even the largest generator units contemplated are limited by reasonable subtransient reactances. For example, a conventional 360-mva generator having a conservatively assigned subtransient reactance value of 9 percent would have a short-circuit value of 4000 mva. Adding an 8 percent reactance for an interposing generator transformer would reduce the short-circuit value to less than 2100 mva. Since the larger machines now being employed have substantially larger



LARGEST GENERATOR RATINGS on order today are over 250 percent higher than those ten years ago. The maximum voltage level of the largest machines has held constant through this period. **(FIG. 1)**



TRANSMISSION BREAKER MVA RATINGS are almost ten times higher than they were ten years ago. These maximum ratings are more than sufficient to handle any system fault. **(FIGURE 2)**

subtransient values than 9 percent, and the transformer reactance is rarely less than 8 percent, the maximum system fault current that could flow in generator and generator transformer will be even less. Consequently, the size of the generator circuit breaker is determined by the available short-circuit power from system interconnections and the parallel connections from other generators within the same station.

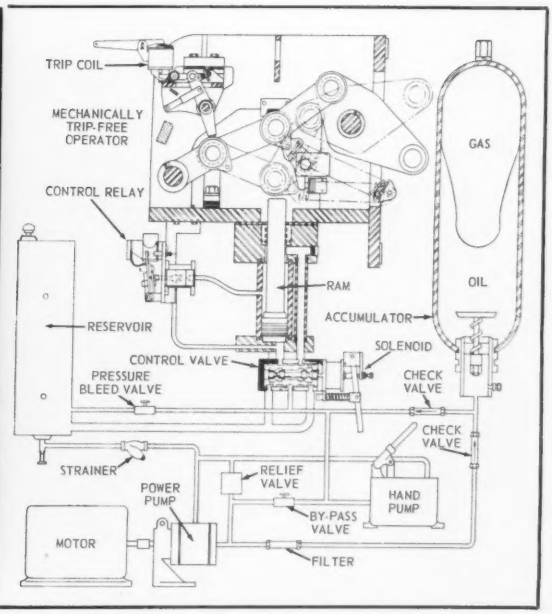
Figure 2 shows the growth in breaker interruption capacity and the ratings now available as standard. These breakers have been developed to meet existing system requirements for interruption capacities of 10,000 mva and up at the transmission voltage levels.

Breaker ratings are ahead of system needs

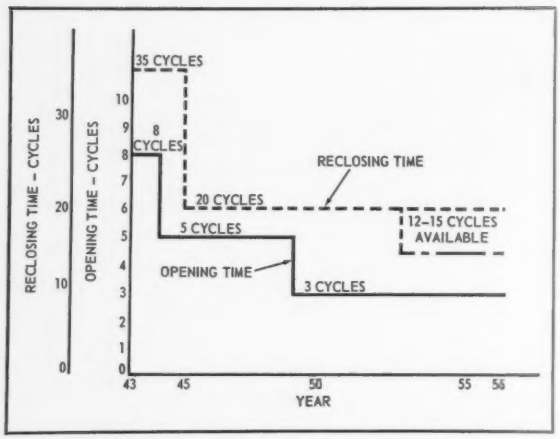
This growth of breaker interrupting capacity is phenomenal when one considers that as late as 1941 a 3500-mva, 5-cycle breaker was considered the ultimate. Today breakers are built from 5000 mva to 25,000 mva and clear the circuit in less than three cycles.

Transmission breakers 15,000 mva, 2000 amperes, 138 kv are now being considered, while transmission breakers rated 10,000 mva, 138 kv and above are available with a full-load current rating of 1600 amperes. The full-load current of the 360-mva generator at 138-kv voltage level is 1500 amperes. For this rating the 1600-ampere generator breaker allows a sufficient margin for possible overloads.

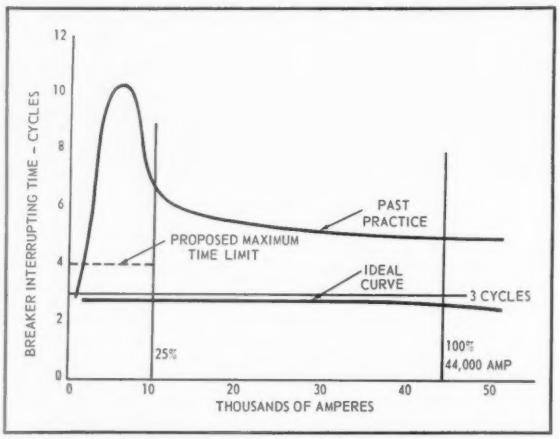
COMPLETE OPERATOR with control, *Pneu-Draulic* closing device and operator mechanism are enclosed in single cabinet. All parts are readily accessible on these large transmission breakers. **(FIG. 3)**



SIMPLE HYDRAULIC CIRCUIT, using an accumulator for stored energy, actuates breaker's time-proven mechanically trip-free mechanism for fast closing and reclosing of large breakers. **(FIG. 4)**



OPENING AND RECLOSING TIMES of transmission breakers have been drastically reduced in the past few years. **(FIGURE 5)**



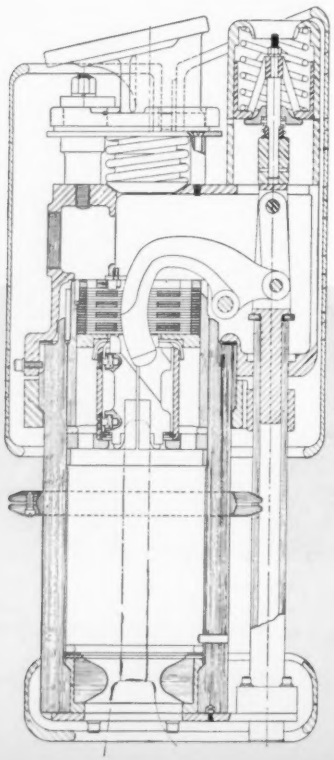
FASTER OPENING at reduced currents may be expected as transmission breakers approach the ideal curve. **(FIGURE 6)**

It is feasible to build these breakers to carry 2000 amperes continuously when the demand arises. A 2000-ampere, full-load current breaker would be capable of handling a 400-megawatt generator.

Breakers are faster

The interest of the utilities in minimizing system outages and improving system stability has caused the breaker manufacturers to make faster breakers while meeting the need for greater interrupting capacities. Figure 3 shows a 10,000-mva breaker just prior to shipment. The hydraulic circuit for the *Pneu-Draulic* operator, a recent and important development for large breakers, is illustrated in Figure 4. Figure 5 shows the trend toward faster interrupting time of these breakers from 8 cycles to 5 cycles to 3 cycles. Typical interrupting time for large breakers is shown in Figure 6. Figure 7 shows the *Turbo-Jet* interrupting device used in breakers rated 10,000 mva and up.

To keep ahead of power system growth, breaker design engineers have taken advantage of new materials and applied the latest scientific developments in their mechanical, electrical, and hydraulic schemes. The application of these developments has resulted in greater strength with less mass, and in improved closing-power supplies and operator mechanisms.



***TURBO-JET* INTERRUPTING DEVICE,** used in large three-cycle oil circuit breakers, makes use of tulip and bayonet type contacts. Cut-away drawing shows construction. Parts of one unit shown above were removed to reveal upper portion of the interrupting device. **(FIG. 7)**

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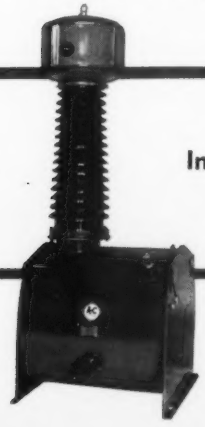

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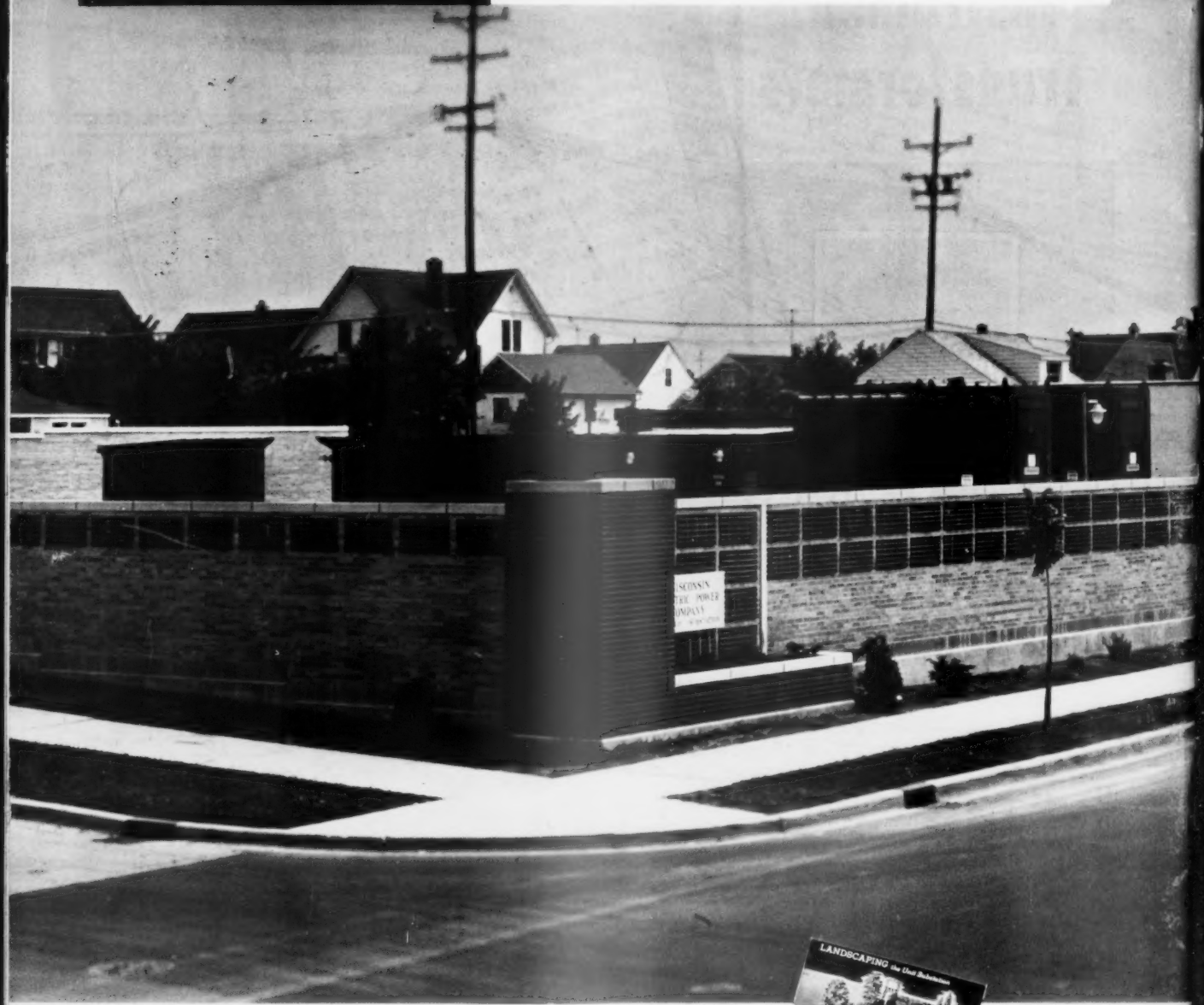

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